

CRANFIELD UNIVERSITY

ROGER BAILEY

THE EVOLUTION OF FIXED WING AIRCRAFT HANDLING
QUALITIES DURING THE FIRST FIFTY YEARS

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING

MSc BY RESEARCH
Academic Year: 2023 - 2025

Supervisor: Simon Place
Associate Supervisor: Mushfiqul Alam
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ABSTRACT

The study investigates the evolution of the handling qualities of British aircraft between 1910 and 1950. In this era, before the implementation of rigorous airworthiness requirements, many aircraft were deficient in some form or another by modern standards. Such deficiencies may not be anticipated or understood by today's pilots who wish to fly old aircraft and this can result in mishandling, loss of control and ultimately accidents.

This study uses a combination of quantitative analysis and qualitative judgements from historical sources to investigate vintage aircraft flying qualities. It includes analysis which makes a novel contribution to this area of aeronautics.

Contemporaneous pilot accounts reveal that the understanding of the 'mechanics of flight' was generally poor. Legacy flight instructor handbooks show that early flying 'folklore' tends to outlive its usefulness and also reveal deficiencies in stability and control in the contemporary training aircraft.

An analysis was conducted using a group of 41 aircraft, which formed a representative example of British aircraft of the era. The longitudinal, directional and lateral, stability and control parameters were estimated using generic equations and known aircraft geometry.

Today's certification specifications are used as a benchmark against which the vintage aircraft¹ in this study are assessed for non-compliances. This analysis shows an inverse near-linear relationship between the year of design of an aircraft and the number of deficiencies it exhibits.

Other factors that can affect handling qualities including the cockpit interface, and the aircraft environment are discussed. An analysis of these factors is made to highlight the higher risk areas when flying the vintage aircraft of the era.

¹ In this thesis the expression 'vintage aircraft' refers to aircraft which were originally designed during the period 1900-1950.

The findings are used to develop guidance for a modern pilot², planning to fly a strange vintage aircraft for the first time.

² For the purposes of this study a 'modern pilot' is one who has been trained using aircraft certificated to modern certification standards or their military equivalent.

Keywords:

stability, control, directional, evolution, handling, lateral, longitudinal, pilot, qualities, tail volume, vintage

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I would like to express my appreciation to the Royal Air Force, a meritocracy which took in an uneducated schoolboy and thereafter provided opportunities to progress through an aviator's career including as an exchange student with the United States Air Force Test Pilot School. During that career I wish to extend my thanks to the pilots and crew members who trained and guided me.

I will always be grateful to the late Professor Denis Howe, Head of the College of Aeronautics and Chief Designer, who took me on as his Chief Test Pilot, and my professional colleagues including, Alastair Cooke Christopher Daggett, Martin Eshelby the late Michael Cook, for their guidance and support.

Thanks must go to The Shuttleworth Trust without which this study would not have been possible. With the Shuttleworth Collection I was able to fly and, in many cases, test aircraft from the first fifty years of powered flight under the tutelage of Chief Pilots; John Lewis, Andrew Sephton, Trevor Roche and Paul Stone. It was this experience which motivated my research which I would like to dedicate to the memory of the late Trevor Roche who lost his life flying a vintage aircraft.

Finally, I wish to thank my wife D', for her support in allowing me to indulge myself in undertaking this study

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LIST OF ABBREVIATIONS

A	Aspect ratio (suffix indicates which surface)
$A_{e\ V. \ TAIL}$	Effective aspect ratio of vertical tail
A	Aileron (as a suffix)
a	Lift curve slope (suffix indicates which surface)
ACA	Advisory Committee for Aeronautics
agl	Above ground level
AIC	Aeronautical Information Circular
ANEC	Aerial Navigation Engineering Company
AP	Air Publication
ARC	Aeronautical Research Committee
ARI	Aileron Rudder Interconnect
B	Biplane
b	Span (suffix indicates which surface)
BCAR	British Civil Airworthiness Requirements
BHP	Brake horsepower
c	Chord (suffix indicates which surface)
$\bar{c}$	Mean aerodynamic chord (MAC)
CAA	Civil Aviation Authority (UK)
CFS	Central Flying School
c.g.	Centre of gravity
CS	Certification Specifications (EASA)
deg °	Degree
deg/sec	Degrees per second
DH	De Havilland (DHC De Havilland (Canada))
E	Elevator (as a suffix)
E.A.	Enemy Aircraft
EAS	Equivalent air speed
EASA	European Aviation Safety Authority
FQ	Flying qualities
ft	Feet
ft ²	Square feet
ft/min	Feet per minute

g	Acceleration due to gravity (32.2 ft/sec ²)
G	Biplane gap
HP/hp	Horsepower
IAS	Indicated air speed
I _{xx}	Moment of inertia in roll
I _{yy}	Moment of inertia in pitch
I _{zz}	Moment of inertia in yaw
k ₁ /k ₂	Spanwise location of inner (k ₁) and outer (k ₂) end of the aileron
k	Munk's Span Factor
kg	Kilogramme
kt	Knot
L	Lift force
ℒ or ℓ	Rolling moment
L&P	London & Provincial flying school at Hendon
L/D	Lift to drag ratio
lb	Pound (weight)
lbf	Pound (force)
lb/sq.ft.	Pressure in pounds per square foot
M	Pitching moment
M	Monoplane
m	Mass
m.p.h.	MPH Miles per hour
N	Yawing moment
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics & Space Administration
NLG	Nose landing gear
p	Roll rate
PA	Piper Aircraft
PIO	Pilot induced oscillation
q	Dynamic pressure (suffix indicates which surface)
q	Pitch rate
R	Rudder (as a suffix)
r	Yaw rate

RAE	Royal Aircraft Establishment
RAF	Before 1918 Royal Aircraft Factory after 1918 Royal Air Force
R&M	Reports and Memorandum
RFC	Royal Flying Corps
RPM	Revolutions per minute
s sec	Second
smc	Standard mean chord
SPPO	Short period pitching oscillation'
S	Area (suffix indicates which)
TLG	Tail landing gear
TN	Technical note
USAFTPS	United States Air Force Test Pilot School
V	Velocity
VMC	Visual meteorological conditions
VMC	Velocity Minimum Control
V_A	Manoeuvre speed
V_H	Maximum airspeed in level flight
V_S	Stalling speed
V_{S1}	Stalling speed in stated configuration
V_{S1g}	Stalling speed in flight at 1g
V_{S0}	Stalling speed in the landing configuration
∇	Volume coefficient (suffix denotes which)
∇_A	Volume coefficient of ailerons
∇_E	Volume coefficient of elevator(s)
∇_F	Volume coefficient of fin(s)
∇_{HT}	Volume coefficient of complete horizontal tail
∇_T	Volume coefficient of tailplane(s)
∇_R	Volume coefficient of rudder(s)
Y	Side force
y	Lateral/spanwise distance
Wt w	Weight
WW1	First World War 1914-1918
WW2	Second World War 1939-1945

C_L	Coefficient of lift
$C_{\mathcal{L}}$	Coefficient of rolling moment
$C_{\mathcal{L}p}$	Coefficient of rolling moment due to roll rate
$C_{\mathcal{L}r}$	Coefficient of rolling moment due to yaw rate
$C_{\mathcal{L}\beta}$	Coefficient of rolling moment due to sideslip angle
$C_{\mathcal{L}\delta_a}$	Coefficient of rolling moment due to aileron deflection
$C_{\mathcal{L}\delta_r}$	Coefficient of rolling moment due to rudder deflection
$C_{\mathcal{M}}$	Coefficient of pitching moment
$C_{\mathcal{M}\alpha}$	Coefficient of pitching moment due to angle of attack
$C_{\mathcal{M}C_L}$	Coefficient of pitching moment due to lift coefficient
$C_{\mathcal{M}q}$	Coefficient of pitching moment due to pitch rate
$C_{\mathcal{N}}$	Coefficient of yawing moment
$C_{\mathcal{N}\beta}$	Coefficient of yawing moment due sideslip angle
$C_{\mathcal{N}\delta_a}$	Coefficient of yawing moment due to aileron deflection
$C_{\mathcal{N}\delta_r}$	Coefficient of yawing moment due to rudder deflection
$C_{\mathcal{N}p}$	Coefficient of yawing moment due to roll rate
$C_{\mathcal{N}r}$	Coefficient of yawing moment due to yaw rate
C_Y	Coefficient of side force
α	Angle of attack
β	Angle of sideslip
Δ or δ	Change
ε	Downwash angle
ϕ	Angle of roll
$\Gamma - \Gamma_{\text{eff}}$	Dihedral angle - Effective dihedral angle
γ	Flight path angle
η	Elevator angle
η	Tail efficiency (suffix denotes which surface)
λ	Taper ratio
μ	Relative density
$\mathcal{L}_{\beta}$	Rolling moment due to sideslip

$\mathcal{L}_v$	Rolling moment due to side velocity
θ	Pitch attitude
ρ	Air density
τ	Control effectiveness (suffix denotes which control surface)
ψ	Angle of yaw
$\dot{\psi}$	Rate of change of angle of yaw (earth axis)

FOREWORD

The researcher trained as a pilot in the Royal Air Force (RAF) and after three Lockheed Hercules C-130 squadron tours then trained as a qualified flying instructor (QFI) at the Central Flying School (CFS) subsequently attaining an A2 category. Next, as an exchange student he trained as an experimental test pilot at the United States Air Force Test Pilot School and later served as a test pilot attached to the Royal Aircraft Establishment. After leaving the RAF he became the Chief Test Pilot of the College of Aeronautics at Cranfield University. At about the same time he became a volunteer pilot with the Shuttleworth Trust which owns and operates a collection of nearly fifty vintage aircraft ranging from a 1909 Bleriot XI to a 1950 DHC Chipmunk. The researcher has flown virtually all the aircraft in the Shuttleworth Collection and many other vintage types and became intrigued by the variation in aircraft handling qualities. See Appendix F. The researcher's access to these aircraft presented a near unique opportunity to attempt to investigate and compare the characteristics of aircraft from an era where although, handling qualities existed, the subject was neither defined nor documented.

1 INTRODUCTION

Aircraft handling qualities are those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the flight task. It is an amalgam of the static and dynamic stability of the aircraft, its controllability and so a certain degree its performance and how a typical human pilot will interact with those characteristics to achieve safe and efficient flight. Since the 1970s the most used method for measuring aircraft handling qualities is the Cooper Harper Handling Qualities Rating Scale. (Cooper & Harper, 1969) In this method the investigator defines a relevant flight task, which the test pilot flies and then, by using the HQR scale in a disciplined manner, assigns a rating between 1 and 10. These are closed loop tasks because it is necessary for the pilot to be controlling the aircraft to a high degree of precision to uncover undesirable characteristics. That rigorous method of assessing handling qualities is not possible when investigating flight characteristics from historical accounts and is often impractical when flying vintage aircraft today due to the absence of instrumentation of sufficient resolution. However, all the aircraft addressed in this study are light aircraft of conventional design with low moments of inertia and with reversible control systems. Therefore, a reasonable indication of the likely handling qualities can be inferred from the estimated levels of static stability and the controllability characteristics since the short period dynamic modes are almost invariably well damped and the long period modes are less critical. Historical accounts by pilots, scientific reports where these are available.

It is now recognised that powered flight began in December 1903 in the USA when the Wright brothers made sustained flights in their 'Flyer'. In Europe powered flight lagged somewhat and it was not until October 1906 when Santos Dumont flew his 14 bis for 200 ft. France became the de-facto epicentre of flying but the focus was on aircraft having inherent stability until the Wright brothers demonstrated fully controlled flight to the European aeronautical intelligentsia at Le Mans in August 1908. Between then and the onset of World War One many speculative aircraft were built, and some flew. Because aircraft constructors were

‘feeling their way’ there was little standardisation of design and the complete panoply of aircraft configurations were tried including monoplanes, biplanes, multi-planes – with and without dihedral, tail to rear, canard, lifting tail, fixed fin, all flying rudders, blinkers, balancers, ailerons and wing warping. Accidents were relatively commonplace over the period covered by this study. See Appendix B for a table of aircraft accidents recorded between 1910 and 1939 – not including losses on active service. From the source [Fatal air accidents in Britain: statistics](#), it was possible to identify which accidents were attributed to loss of control such as stalling, spinning or uncontrolled sideslip and this data is shown in the following plots which illustrate the toll taken by a combination of deficient handling qualities and perhaps inadequate pilot training.

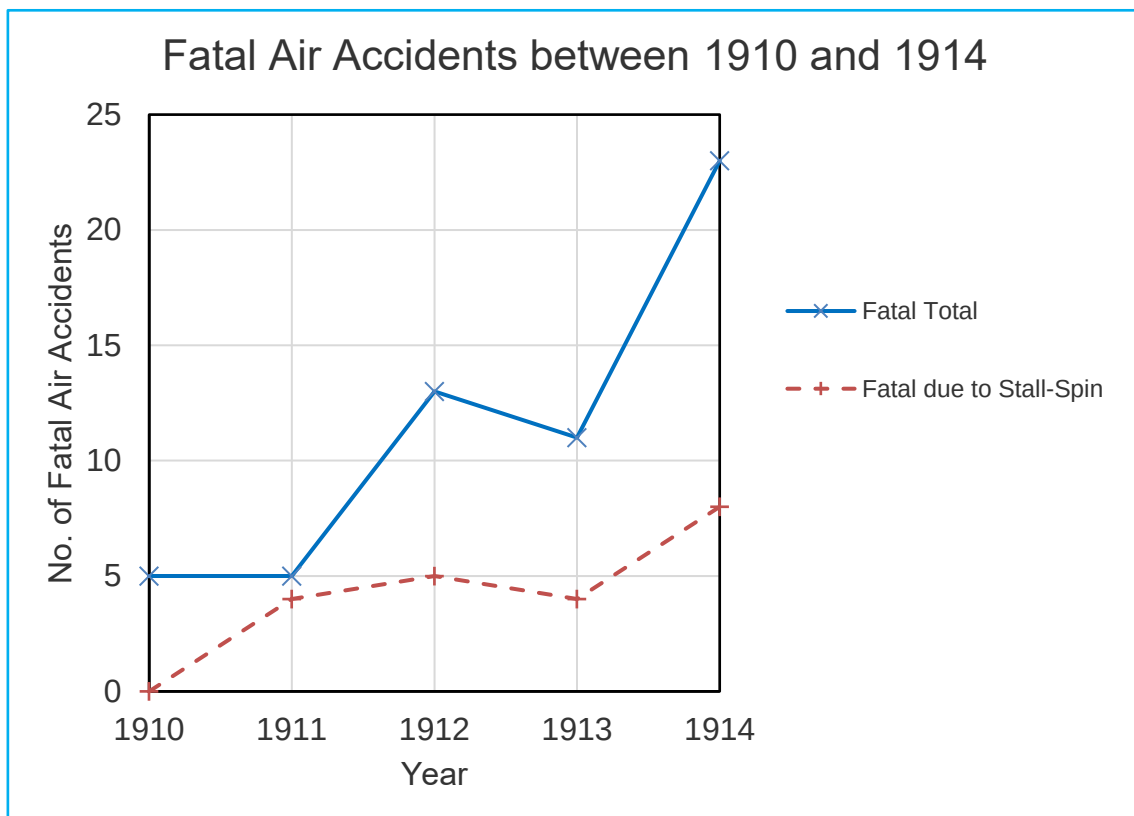


Figure 1-1 - Fatal Air Accidents 1910-1914

Figure 1-1 shows that the number of fatal accidents in Britain between 1910 and the onset of WW1 to be relatively modest, probably reflecting that the performance of these early aircraft limited their height and speed allowing many pilots to survive the many (largely unrecorded) crashes. The proportion due to

stall/spin was also relatively modest. As WW1 began and military flying and associated flying training ramped up the rates showed a marked increase.

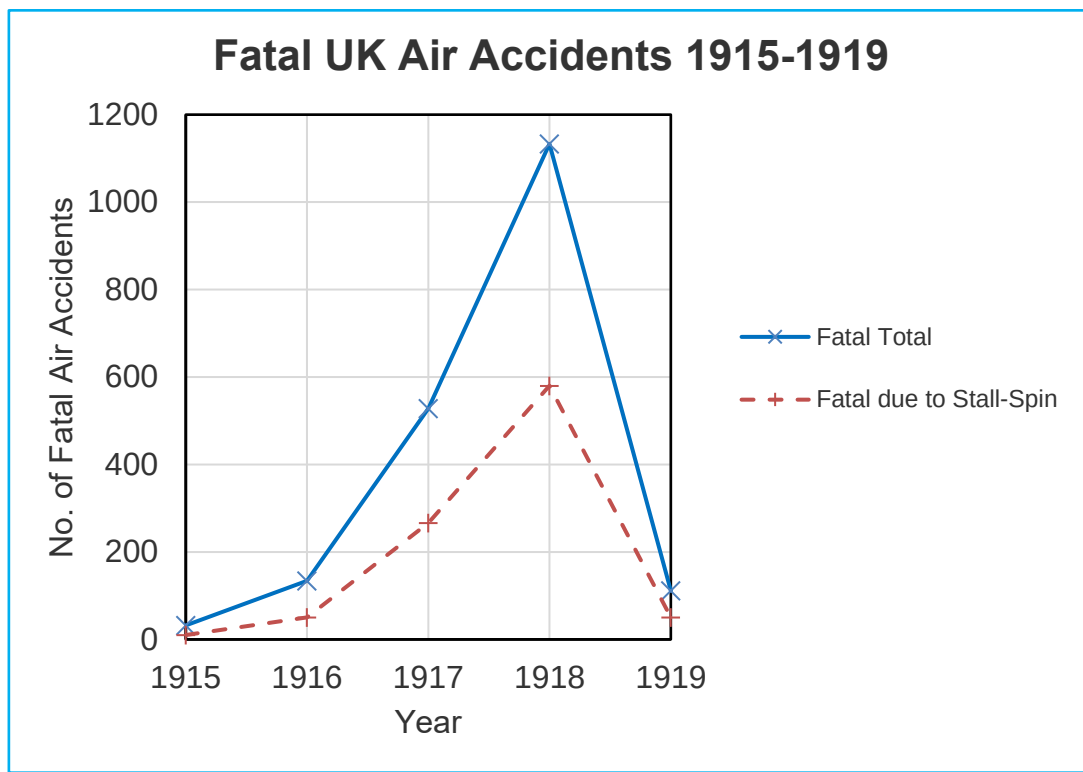


Figure 1-2 - UK Air Fatal Air Accidents 1915-1919

Figure 1-2 covers the period of the Great War and Armistice but does not include losses on active service overseas. The accident rate then exploded by many orders of magnitude and most of these were likely related to pilot training. Military pilot training would have all but stopped after the Armistice and the reduction is shown on the graph. Stall/spin related fatal accidents were the largest single causal factor.

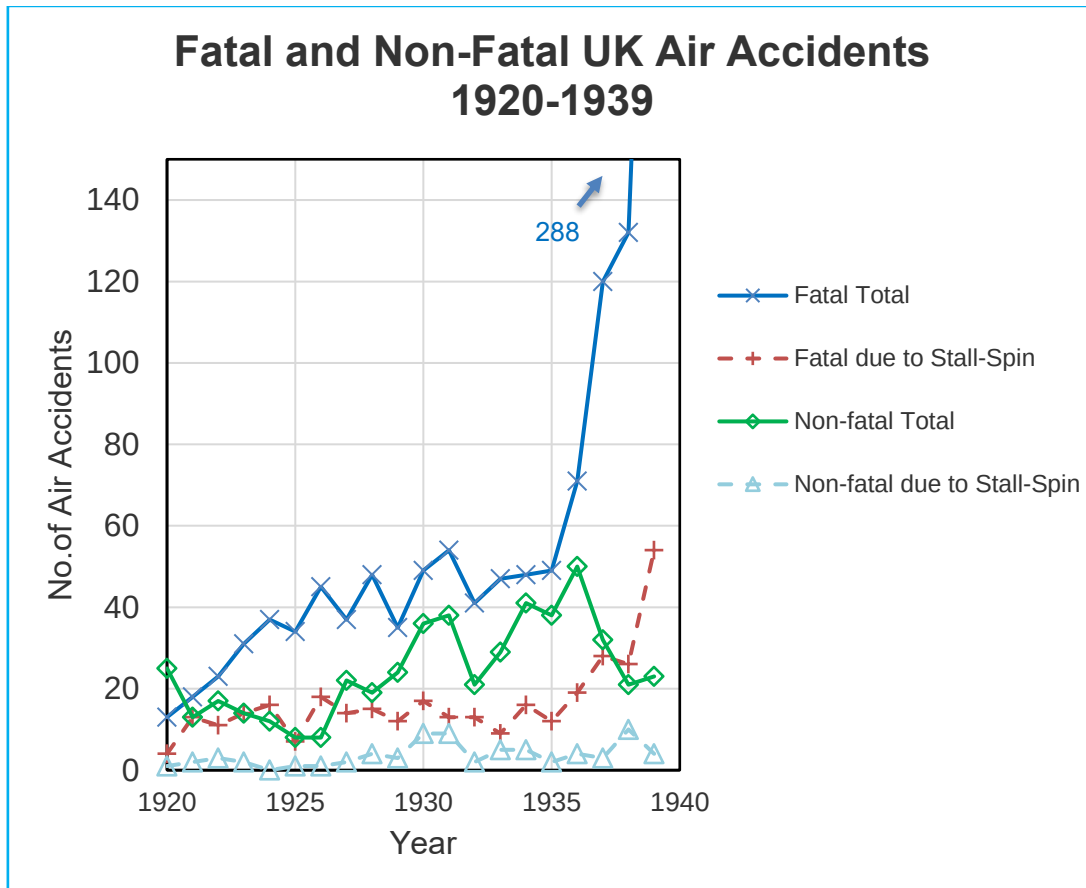


Figure 1-3 - Fatal and Non-Fatal UK Air Accident – 1920-1939

Figure 1-3 shows the inter-war period for both fatal and non-fatal accidents and proportions of each attributed to the stall/spin. This shows that total number of fatal accidents increased steadily over the period 1920 to 1935 probably reflecting the growth in aviation generally. From 1936 on, as the military once again gear-up for the coming war, the rate increased rapidly to reach 288 by 1939. The proportion of fatal accidents attributed to stall/spin represented about one third of the total. Non-fatal accidents were also recorded in this period and the rate was similar to the fatal rate until 1936 when it fell suddenly. This may be because in this period the bulk of the aviation activity was related to military training and the type of accidents were less 'survivable'. Similarly, the number of non-fatal accidents attributed to the stall/spin was a much lower proportion of the total indicating that survivable stall/spin accidents were unusual.

These tragic accidents illustrate that even in peacetime these aircraft suffered many loss-of-control accidents. When aircraft from that period are flown today,

they are just as deficient as they were when they entered service and today's pilots, while adequately trained to fly modern aircraft, may not have the skill sets these vintage aircraft require. That concern and how it might be 'quantified' and mitigated is the motivation for this research project.

For readers unfamiliar with this era of aviation Figure 1-4 shows some examples of aircraft layouts referred to the study.

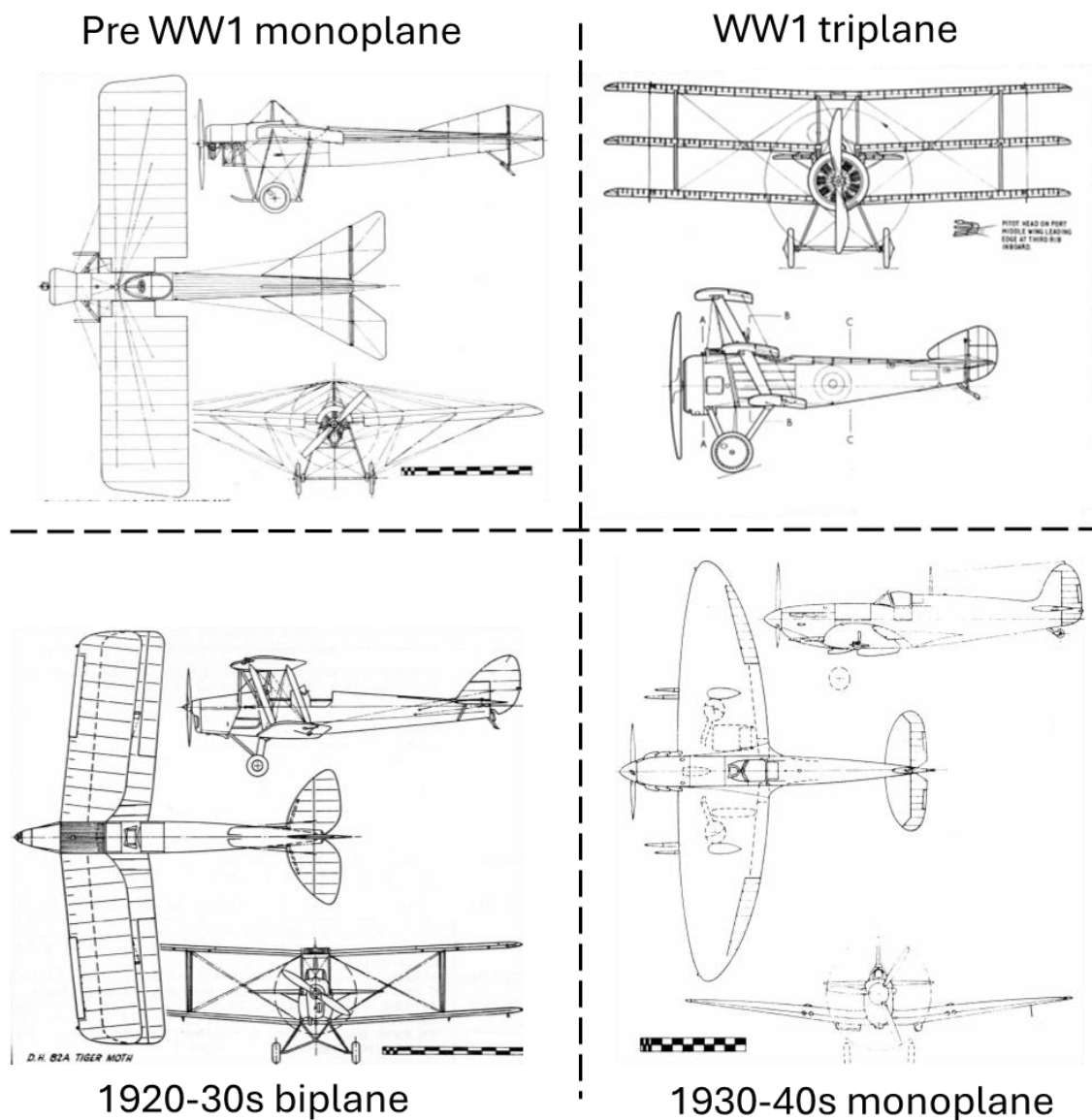


Figure 1-4 - Example Aircraft Layouts

There were several fatal accidents resulting from structural failures of pre-WW1 monoplanes and as a result Britain became firmly wedded to the more robust

biplane configuration which endured for more than a decade after the Armistice. To keep the aircraft industry ticking over during the interwar period the UK Air Ministry typically ordered unprofitably small production runs from a multiplicity of firms, but this policy tended to stifle innovation. To keep down complication and cost the biplanes of this era were not equipped with flaps for landing or wheel brakes to assist steering on the ground. These commercial and design decisions had unintended consequences as the aircraft had to be sideslipped when gliding down to land and had to be taxied using the rudder control only – this resulted in aircraft with small, fixed fins and very large rudders; a ratio of rudder to fin being around 4:1 typically. This vertical tail layout compromised controls-free directional static stability and provided greater rudder control power than needed for most flight phases. This arrangement, often coupled with powerful lateral stability and indifferent roll control power, can make these aircraft more challenging to fly and quite different in this respect to a modern aircraft. Although many of these aircraft would have been considered normal at the time, a modern pilot, accustomed to strong controls-free directional stability inter alia, will find them quirky, disconcerting and in some circumstances, dangerous. By the late 1930s monoplanes were beginning to replace biplanes. The associated higher airspeeds forced an improvement in longitudinal and directional static stability to avoid unintentionally large airflow angles which would result in overstress or structural failures. Even so handling characteristics of the early monoplanes of the 1930's varied considerably, and the accident rate did not reduce markedly.

The intention therefore is to map the evolution of handling qualities, identify trends and areas of handling which a modern pilot might not anticipate before flying a vintage aircraft. Some are forgiving and easy to fly while others can be extremely challenging, particularly if the pilot is not adequately prepared. This inconsistency also poses a threat because a pilot with experience of one easy vintage aircraft may assume that they are all as easy, sometimes evidenced by a typical pilot remark of “Oh it's just another aeroplane”. This level of complacency when applied to vintage aircraft can be problematic.

Between the end of WW2 and the present day there have been too many accidents involving vintage aircraft to list here. However, in more recent years, there have been a number of accidents which serve to illustrate that the characteristics of vintage aircraft are often a contributory cause to loss of control accidents which often involve fatalities. Extracts from these accident reports are shown in Appendix B. Three resulted from a stall/spin, contributory factors being, low excess power, poor longitudinal static stability, lack of stall warning, poor stalling qualities, excessive rudder power and poor lateral control. The other accident resulted from a sideslipping spiral dive, contributory factors being poor directional stability and inadequate lateral control power. Such characteristics are common on many vintage aircraft.

It is hoped that the findings of this study might be used to inform pilots of the unanticipated handling challenges found in some vintage aircraft and thereby reduce the number of such accidents in future.

1.1 The research aim

To investigate how the evolution of British aircraft handling qualities over the first fifty years of powered flight influenced aircraft development and pilot training methods? To investigate whether knowledge of that evolution can be utilized to improve safety for pilots who fly genuine or replica vintage aircraft today?

The study examines forty vintage British aircraft owned and operated by The Shuttleworth Collection which is based at Old Warden in Bedfordshire and are all airworthy and accessible to the researcher to take dimensions to support the analysis. The Collection focus is on British aircraft, of the aircraft studied all are of British origin except for a Russian Po-2 and an US Piper Cub. It is recognized that this is a limitation as aircraft evolution in some other nations progressed differently due to the local physical and/or political environment.

1.2 Objectives

1. Identify potentially challenging handling deficiencies of earlier aircraft by analysing and interpreting contemporaneous pilot reports and by analysing

and interpreting legacy pilot training syllabi to identify ‘myths’, and obsolete and ill-informed methods.

2. Conduct an analysis to estimate the open-loop stability and control characteristics of a representative sample of ‘vintage’ aircraft to determine how such characteristics evolved during the first fifty years.
3. Identify those aspects of modern certification specifications with which vintage aircraft do not comply and the relevance of such non-compliances to their safe operation today.
4. By using the findings of this study identify aspects of vintage aircraft handling qualities that could cause pilots trained on modern aircraft to lose control, and to offer guidance and suggest mitigation techniques.

1.3 Structure of the Thesis

To answer the research question several areas are investigated. In Chapter 2 qualitative data from contemporaneous accounts written by pilots of early aircraft are cited and analysed, and pilot training methods are examined to establish how training was adapted to cater for growing knowledge and changing aircraft characteristics. In Chapter 3 relevant longitudinal, directional and lateral characteristics of a group of 41 airworthy vintage aircraft which span the entire period of interest are investigated using well known generic relationships so that the evolution of the characteristics is shown. Modern certification standards are examined to Chapter 4 to identify requirements with which vintage aircraft do not comply, and the significance of non-compliances is discussed. The ground handling challenges of typical vintage aircraft are also discussed. Chapter 5 investigates other factors which affect a pilot’s impression of an aircraft’s handling qualities. Chapter 6 offers some guidance on how a modern pilot might prepare for a first flight in an unfamiliar vintage aircraft. The thesis summary and conclusions are in Chapter 7. Supporting appendices follow.

1.4 Aeroplane Handling Characteristics

1.4.1 The Ideal Aeroplane

To appreciate the significance of the characteristics of vintage aircraft that 'modern' pilots will often find challenging, or sufficiently non-intuitive to cause significant distraction, it is necessary to understand what the characteristics of an 'ideal' aircraft should be. This discussion is based around a small, simple, un-augmented aircraft certificated to modern standards which has benefited from the handling qualities development following WW2. The characteristics will be discussed under the same headings³ as used later in the thesis to discuss vintage aircraft handling deficiencies.

1.4.1.1 Ideal Control Harmony

An ideal aircraft will have good control harmony, which is where the forces required for lateral, longitudinal, and directional control are in the ratio of 1:2:4.

1.4.1.2 Ideal Longitudinal Characteristics

The ideal aircraft will have a moderate amount of longitudinal stability, meaning that if it is disturbed from a trim condition it will return to that trim condition quickly without pilot input and without excessive oscillations. This implies controls free static, manoeuvre and dynamic stability. An aircraft with this stability can be trimmed to maintain an angle of attack or an airspeed and will automatically maintain that flight condition until the pilot demands a change. In addition to stability the ideal aircraft requires adequate longitudinal controllability so that when the pilot wishes to change the longitudinal flight condition with the elevator this can be done smoothly, with a force which is not too small or too large, and without encountering a control stop. When manoeuvring in pitch the response must be essentially linear to be sufficiently predictable to the pilot, and any resulting short period oscillation must be heavily damped. The control force needs

³ Longitudinal characteristics can usually be treated in isolation without serious error whereas lateral and directional characteristics cannot be treated entirely independently but it is often convenient to describe them separately and then discuss those areas where cross-coupling is significant.

to be appropriate to the role of the aircraft so that it is not too easy to stall the aircraft nor to easily overstress its structure. There must be a trimming device which the pilot can use to remove residual control forces as flight conditions are changed and this system must be capable of removing residual control forces throughout the speed range and throughout the permitted range of centres of gravity.

1.4.1.3 Ideal Directional Characteristics

The ideal aircraft exhibits strong directional static stability meaning that it will orient itself into the relative air flow to remove any sideslip automatically without pilot input. This characteristic is very different in many vintage aircraft so to indicate modern, post WW2 design philosophy the following extracts are offered.

‘Sideslip can be used to increase the airplane’s drag and thereby its flight path angle during an approach for a landing, may also be useful in accomplishing smooth aerobatics such as slow rolls, and finally can help out during flight with asymmetric power. However, in general it can be said that in almost all flight conditions it is advantageous to maintain zero sideslip, and the easier it is for the pilot to hold zero sideslip the better he will like the flying qualities of his airplane.’

(Perkins & Hage, 1949, p. 315)

‘Actually, if an airplane has an adequate margin of static directional stability, the rudder may be eliminated.’

(Dommasch et al., 1951, p. 481)

An aircraft with the amount of directional static stability suggested in these quotes would require no, or very little, rudder input from the pilot to roll into, maintain and roll out of a banked turn making such manoeuvres easy to fly. Furthermore, turns can be accomplished safely should the rudder control become inoperative.

Notwithstanding this high level of directional static stability, in practice a rudder control is still necessary for the manoeuvres mentioned in the quote and for others, but the pilot will expect the rudder control force to be the highest of the

three primary controls (to act as a deterrent to sideslipping) and that if no rudder input is made, the aircraft will fly itself without sideslip. When inputs are made, or when gusts upset the equilibrium, any resulting oscillations must be well damped. In addition to the yaw/sideslip created when the rudder is used it may also cause the aircraft to roll through several 'cross-coupling' effects such as roll due to yaw, roll due to sideslip, and roll due to rudder deflection. The rudder will never be so powerful that the rolling moments it generates are greater than the rolling moment that can be generated by the lateral control system.

1.4.1.4 Ideal Lateral Characteristics

The lateral characteristics are those associated with mostly with rolling motion. As in the longitudinal and directional characteristics discussed above there is a consideration of sufficient stability and of adequate control and ease of handling. In the longitudinal and directional cases, it is the response to an off-trim angle of attack or angle of sideslip respectively that provides the corrective action following a disturbance to the desired flight condition. In this case whenever the aircraft rolls or is banked over a sideslip results and a well-designed aircraft will respond by rolling to eliminate that sideslip in a way that is usually referred to as dihedral effect or lateral stability.

'The phenomena of rolling moment due to sideslip is termed dihedral effect and is not a static stability in the true sense of the word.'

(Perkins & Hage, 1949, p. 341)

Notwithstanding that, the ideal aircraft will exhibit an appropriate amount of dihedral effect suitable for its role. This will allow the pilot to fly hands-off the lateral control for a reasonable amount of time to attend to other tasks while using the rudder to maintain control of the bank angle. It may prevent spiral dive, and it will also allow turns to be made safely if the lateral control became inoperative.

The lateral control system (usually in the form of ailerons) is used when the pilot wishes to roll the aircraft. The ideal response would be one of pure roll during which no yaw or sideslip is generated. If unwanted yaw or sideslip is generated the pilot must use the rudder to stop it and applying such compensation requires

considerable anticipation, skill and continuous practice. A pilot will much prefer as aircraft which can be rolled up to its maximum rate with no rudder input necessary. Modern aircraft which have strong directional static stability and low to moderate dihedral effect typically approach this ideal although a propeller usually introduces asymmetries which can make this ideal harder to achieve in practice.

1.4.1.5 Cross-coupling characteristics

This relates to a situation when a desired response in one direction also results in a, usually, undesired effect in another. These cross-coupling effects generally increase pilot workload as usually they must be eliminated by additional pilot control inputs. With the notable exception of rolling moment due to sideslip the pilot will prefer an aircraft with no cross-coupling effects and while this is difficult to achieve many of the effects have been ameliorated through good design practice since WW2.

1.4.2 The Vintage Aeroplane

In contrast to the ideal characteristics described above most vintage aircraft fall below that ideal and, in some aspects, so far below as to be difficult to control at least until a pilot gains extensive experience of the particular challenges. On first acquaintance a pilot, more accustomed to the relatively carefree handling of modern aircraft, may lose control before he can adapt to the characteristics.

In the very early days of powered flight the protagonists tried various solutions in order to fly at all and like any evolutionary process many were failures and a few ultimately succeeded. These early aircraft had very little excess power, so they flew low and slow. They were likely to be unstable in one or more axes needing constant pilot attention or, perhaps they could be overly stable in one or more axes, compromising controllability. There were different philosophies on how an aeroplane was turned. Some favoured aeroplanes with little or no directional or lateral static stability to enable wings-level skidded turns, while others preferred banked turns. The use of rudder deflection to initiate and maintain a turn was virtually universal in Europe – lateral control was something of an afterthought.

Aircraft surviving from this period present significant handling challenges to a pilot accustomed to the 'ideal' aeroplane described above, who may well lose control by using the lateral and directional controls inappropriately particularly if simultaneously distracted by longitudinal instability, very poor performance or poor near stall characteristics.

The First World War accelerated aircraft development, especially in performance and weight carrying, but many aircraft of this era were longitudinally unstable and most directional unstable - controls free. Some exhibited lateral stability, some not. The rotary engine rose to prominence during this time and the precession, resulting from its rotating mass, complicated handling and, in extreme cases, rendered the aircraft virtually unflyable by a novice pilot. Aircraft surviving from this era, or reproductions thereof, can also be extremely challenging for a pilot trained on the 'ideal' aeroplane.

In-flight structural failures of monoplanes in the early days prompted the British authorities to ban it for a period and this locked the British industry to the biplane layout for over a decade after WW1. This, and a reluctance to innovate with such things as wheel brakes and landing flaps, resulted in a generation of aircraft with little controls free directional stability and rather too much directional control. This combination, coupled with generous lateral stability and limited lateral control power, can prove challenging to a pilot expecting 'ideal' aeroplane responses.

Aircraft development was slow between the wars but when at last the monoplane was rehabilitated the use of wheel brakes and landing flaps became commonplace. Such enhancements allowed improvements in the lateral and directional characteristics, although some aircraft remained potentially dangerous outliers which a pilot, accustomed to the 'ideal' aeroplane, will find challenging in specific parts of the flight envelope.

The Second World War prompted another spur to rapid development but once again it was aircraft performance that drove innovation. The higher speeds now achievable brought new structural concerns and good directional static stability became more important. Extremely low values of stick force per 'g', seen as aiding manoeuvrability, were commonplace on British fighter types requiring very

delicate handling, particularly at high airspeed. With the advent of the WW2 fighter a new level of performance arrived through the development of powerful engines which were heavy and required a large mass of fuel, often carried in the fuselage. This increased the pitching and yawing moments of inertia such that the damping of the short period oscillations started to be a concern. The powerful engine driving a large diameter, heavy, variable pitch propeller once again introduced destabilising effects mirroring in part those associated with the WW1 rotary engine. These effects include a torque reaction which causes the aircraft to roll in the opposite direction to the propeller when power is changed, a helical propeller tip vortex which changes the angle of attack at the fin causing a yaw, an asymmetric blade effect which causes a yawing moment and precession which cross couples a yaw to a pitch and vice versa. In addition, the propeller normal force generated at high power also compromises the already low longitudinal static stability at high angles of attack. These effects, which challenged even the expert pilots during WW2 especially for weapon aiming, make such aircraft seem unpredictably tricky to someone accustomed to an 'ideal' aeroplane.

Much research took place leading up to, during, and immediately following WW2 to improve aircraft handling qualities and subsequently this benefitted future designs. By the 1960s-1970s the certification requirements specified the necessary levels of stability and controllability which allowed new aircraft to approach the 'ideal' aeroplane. More recently so-called fly-by-wire aircraft in which handling qualities can be tailored by feedback control, have become the norm for all but recreational purposes, but that development is out with the scope of this investigation.

The handling challenges described above will be discussed in more detail in this thesis to identify 'vintage' aircraft characteristics which will likely be challenging to a pilot accustomed to the 'ideal' aeroplane.

1.5 Literature Review

A literature review was carried out to establish what conclusions had been drawn regarding early aircraft handling qualities. The review examined five eras in the

evolutionary period covered by this study – namely 1900-1914 (pre-WW1), 1914-1919 (WW1), 1920-1935 (Interwar period), 1935-1945 (WW2), and 1946-1951 (aftermath WW2).

1.5.1 1900-1914 (pre-WW1)

Few airworthy aircraft from this era survive today but some reproductions have been constructed and flown for entertainment or research purposes. There were few if any academic papers written in this era. There were some books and articles in periodicals such as *The Aero*, and *Flight*. More recently academic researchers have 'revisited' some of the very early aircraft using wind tunnels, mathematical models and flight simulation.

The first powered flight is recognised as that of the Wright Flyer in December 1903 although in the preceding two years the Wright brothers had successfully flown unpowered gliders and had devised their solution to 3-axis control. As reported in 'The birth of the practical aeroplane: An appraisal of the Wright brothers' achievements was made by (Lawrence, 2004b) Click or tap here to enter text. working at Liverpool University between 2001 and 2010 developed wind tunnel models of the family of aircraft flown by the Wright brothers to gather aerodynamic data from which flight models for a simulator could be devised. These were incorporated into a high-fidelity motion cueing simulator and assessed by test pilots (including the author). This research activity was published in a series of journal papers.

The results showed that the Wright aircraft were all longitudinally unstable, the 1903 Wright Flyer being so unstable that it was extremely difficult to maintain control at all, with a time to double amplitude of 0.41 seconds at 28 knots.(Lawrence, 2004a, p. 227)

The 1939 Flyer also incorporated a wing-warp to rudder interconnect arrangement which was efficacious for straight flights but coupled with their anhedral configuration and warp drag (adverse yaw) produced an unstable roll response which could have proved lethal if the aircraft had been flown any higher than it was.(Lawrence, 2004a, p. 292)

It is fair to say that while the Wright brothers showed the world that fully controlled powered flight was possible their unstable solution was impracticable except at very low airspeed and low height.

For their 1905 trials the Wrights removed the warp to rudder interconnect enabling them to enter, maintain and exit from banked turns under full control but longitudinally their aircraft was still unstable having a pitch time to double amplitude of no more than 1 second. (Padfield & Lawrence, 2005)

In 1908 the Wrights demonstrated their mastery of control, including steeply banked turns, in France before onlooking European aviation pioneers causing Louis Bleriot to aver '*For us in France and everywhere, a new era in mechanical flight has commenced....It is marvellous.*' (Combs, 1979, p. 293)

Having been spurred to greater efforts by the performance of the Wrights, the European aviators made more progress once they unshackled themselves from the utopian dream of complete inherent stability and accepted that it was necessary for pilots to acquire a level of skill to control their aircraft. Aircraft development accelerated as a result, but it would be many years before the disparate stability and control solutions that were devised by manufacturers provided anything approaching good handling qualities – except perhaps by good fortune.

In Aerodynamics Lanchester (1907) and Lanchester (1908) theories of flight and flight stability are developed using an original analytical approach supported by the observation of birds and free flight model aircraft starting in the 1890's. Most of this work predated reports of the Wright brothers' early flights and Lanchester was preoccupied with the concept of inherent stability, probably of necessity due to his use of uncontrolled, free-flight models. He considers an aircraft which has, on any given flight, a '*natural speed*' and that if it finds itself at a higher speed it will climb and if it finds itself at a lower speed it will descend. He also points out that if the angle of incidence of the tail surface is altered this will change the '*natural speed*'. He describes an oscillation in speed, flight path angle and height which he named 'the phugoid' which is cod Latin for 'flight like'. He also posits that if sufficient thrust is provided the aircraft will fly level at its '*natural speed*' and

that if thrust is increased or decreased the aircraft will climb and descend respectively with only minor excursions away from the '*natural speed*'. While this is demonstrably correct the phugoid oscillation can occur only if the aircraft has longitudinal static stability. He also addressed lateral and directional characteristics in his original way, and, on his models, he often used large high aspect ratio vertical fins mounted on the fuselage directly above the centre of gravity to provide 'lateral stability'. In his descriptions he often draws analogies to boat stability and described the possibility of an aircraft capsizing if banked at too great an angle – which was erroneous – or at least for the reasons he believed.

Given his standing his work had a powerful influence in Britain and may have been instrumental in some constructors seeking to provide inherent stability to their creations – not always to advantage. Obsession with phugoid stability would endure into the mid 1940's even though it has been found to have little or no effect on the handling qualities of an aircraft as perceived by the pilot.

Lanchester's analysis methods, while truly original, used somewhat unconventional mathematics which few could follow with ease. It fell to Bryan (1911) a Fellow of the Royal Society, in his book 'Stability in Aviation' to adapt and develop well proven engineering analytical techniques to the aeroplane and from which much of the subsequent study of stability and control has been derived. He addresses longitudinal equilibrium, longitudinal stability for single lifting systems and for double-lifting systems (aircraft with lifting tailplanes), lateral stability with straight planes and with bent up planes (i.e., dihedral).

In the United Kingdom the Advisory Committee for Aeronautics (ACA) 1909-1919 aimed to coordinate aeronautical research activity and publish reports annually. The topics reported on were wide ranging and while none specifically addressed aircraft handling qualities, stability was being investigated throughout the period. Between 1919 and 1945 the ACA became known as the Aeronautical Research Committee (ARC) which continued to produce annual reports and Reports and Memorandum (R&M). R&Ms. In R&M 77 Bairstow et al. (1913) the authors expressed the view that while it was probable that the current knowledge was sufficient to design an aeroplane to have longitudinal and lateral stability it was

possible to make the aeroplane 'over-stable' which led to problems of 'poor steering' and misbehaviour in gusty winds. They also stated that speed stability may be found to be essential while neutral stability in yaw was probably desirable and neutral stability as regards rolling would not be a disadvantage. While this report set down the basis of static stability analysis which is still in use today the interpretation of desirable handling qualities is quite different to the contemporary view. Their views must be seen in the light of aircraft with such low performance that only a very restricted range of airspeed need be contemplated. Speed stability was deemed essential because maintaining the aircraft within the limited speed range available was seen as critical, while neutral directional stability at such low airspeeds was not only manageable by the average pilot and did not compromise the structure but avoided the dreaded spiral dive. The spiral dive was feared because lateral controls (when provided at all) had limited effectiveness. The desired neutral roll stability referred to was seen rightly as better than lateral instability, but it also enabled flat/skidded turns to be made using the rudder without the resulting sideslip producing a rolling moment (through dihedral effect) which would make the aircraft roll into a banked attitude and thereby risk entering a spiral dive. Pilots today are taught a sequential step by step procedure to recover from a spiral dive should they encounter one, but they enjoy effective roll controllability. Bairstow et al. (1913) also address the effect of the gyroscopic effect of the propeller and engine on the aircraft. This is of particular interest in the handling qualities of propeller driven aircraft especially those with high engine power relative to the mass and dimensions of the aircraft and to those equipped with the rotary engine, in which the entire engine spins with the propeller making for a powerful gyroscope. Bairstow et al. (1913) develop the relationships and demonstrate how the precession action turns a yaw rate into a pitching moment and a pitch rate into a yawing moment, both moments being proportional to the product of the moment of inertia of the engine/propeller and its angular velocity and, being inversely proportional to the mass of the aircraft. It suggests that for an aircraft weighing 1300 lb these cross-coupling derivatives for a rotary engine are nearly double that of a stationary engine, on which only the propeller rotates. The significance of cross-coupling to the pilot is

that such effects are usually non-intuitive and therefore increase the level of compensation the pilot needs to achieve the desired result. Bearing in mind that at this stage of aeronautics most turns were flat or nearly so i.e. turns were effected by the pilot yawing the aircraft using the rudder. A rotary engine and propeller spinning clockwise when viewed from the rear will cause the aircraft to pitch downwards when the aircraft is yawed to the right and pitch up when yawed to the left. Given the small speed range available to Pre-WW1 aircraft, if the pitch down was not immediately controlled the aircraft may reach a speed from which recovery is not possible (particularly with aircraft with a lifting tail), whereas if the pitch up was not immediately controlled the aircraft may stall and spin. While early rotary engines were relatively small these effects while dangerous to the neophyte aviator became a nuisance once (or if) experience was gained.

1.5.2 1914-1919 (WW1)

A few examples of airworthy WW1 aircraft survive today, and some reproductions have been constructed and flown for entertainment. Much development took place during WW1 mostly in aspects of aircraft performance such as maximum speed, rate of climb, ceiling, and load carrying. Handling qualities as a technical subject did not exist but sometimes indications of good or bad handling qualities can be deduced from the accounts of military pilots. Towards the end of WW1 as rotary engines became larger with respect to the mass of the aircraft the gyroscopic precession effects mentioned above became very challenging and reportedly caused many loss-of-control accidents among trainees on Sopwith Camel type.

1.5.3 1920-1935 (Interwar period)

Many civilian, and a few military, airworthy aircraft from this era survive today and are flown for entertainment. This period was characterised by very slow development due to a lack of money and the absence of an existential threat to homeland security. Academia was however quite active and the Royal Aircraft Establishment and its equivalents in other nations continued to conduct aeronautical research in many areas but not specifically handling qualities. In the

aviation industry there appeared to be much conservatism for fear of squandering meagre funds, and this may have stultified development.

In Chapter 3 of 'What Engineers Know and How They Know It' (Vincenti, 1990) the author details the development of flying quality specifications in the United States between 1918 and 1943. This is an excellent and insightful piece of engineering history which includes analysis of several important concepts. For designers of machines intended to be operated by humans he points out the importance of recognising the opinion of the human operator as to the ease or otherwise of operation which is by nature subjective. Mistakes and false starts are included because, he asserts, it is through these that learning takes place. He defines 'Flying Qualities' as the *'ease and precision with which a pilot is able to perform the task of controlling the vehicle'* and goes on to say that while such qualities are a property of the aircraft, they cannot be measured other than through the perception of the human pilot. This is significant because pilot perceptions vary depending on inter alia; that pilot's previous flying experience and on the environmental conditions. A designer may aim to incorporate all the best practice ideas with respect to flying qualities but until a pilot flies the aircraft the handling qualities are completely unknown. The pilot's perception is shaped through the movement of, and the forces applied to, the control inceptors and how the pilot perceives the aircraft reaction to them, and this is further influenced by any inherent stability in that axis. He highlights the difference between 'Longitudinal motions' and 'Lateral motions' but, like many commentators, chooses to limit the scope to the longitudinal characteristics. While this approach is understandable it is a pity because some of the more challenging aspects of vintage aircraft arose from their lateral/directional characteristics. He points out that in the US (as in the UK) there was a disconnect between the scientist/engineer school and the constructor/pilot school. The former developing or using sound engineering mathematics while the others relied more on empirical methods and pilot imagination. He reports that the National Advisory Committee for Aeronautics (NACA) sought to correct this disconnect in the years following the First World War by developing a culture of scientists and pilots working closely together on aeronautical research initiatives.

1.5.4 1935-1945 (WW2)

Some airworthy military aircraft from this era survive today and some rebuilds/restorations have been constructed and flown for entertainment. Although WW2 did not officially start until 1939, nations were actively rearming from the mid 1930's which spurred development. During the conflict there was of course an arms race which drove development particularly in terms of performance, often gained at the expense of handling qualities.

1.5.5 1945-1951 (WW2 Aftermath)

A few military, and many civilian, airworthy aircraft from this era survive today. Some reproductions/restorations continue to be flown for entertainment or training. In the immediate aftermath of WW2 academic research continued and was published by NACA and others. In addition, some of the researchers and designers of that era authored aeronautical textbooks based on what had been learned during the war and its aftermath. Some of those reports and textbooks are referenced in this study and are the origin of the equations used in the analysis and are referenced as they arise.

1.5.6 Present day

For many years the United Kingdom Civil Aviation Authority issued an Aeronautical Information Circular entitled 'Piloting Old Aircraft and their Replicas' last updated in 2008. (CAA AIC 86/2008, 2008). It is likely that this document was written originally by the CAA light aircraft test pilot Darrol Stinton, author of three aeronautical handbooks much referenced in this thesis. The circular is well written and lists the likely challenges that a pilot may face when flying old aircraft, but it is necessarily generic and therefore it is not possible for a pilot to apply the advice directly to a particular aircraft.

1.5.7 The research gap

In the first half of the twentieth century any research into aircraft characteristics addressed the aircraft that were available and were mostly focussed on performance. It would not have been of interest for researchers to 'look back'

particularly during those periods when the rate of aircraft development was high and would have been viewed as somewhat indulgent during wartime. Since the end of WW2, with the notable exception of the studies conducted at Liverpool University in the 1990's (referenced above), no research papers which specifically address the handling qualities of archaic/vintage aircraft have been discovered. However, an increasing number of archaic/vintage aircraft are now being flown and so there is no repository of archaic/vintage aircraft handling qualities research that the current operators of such aircraft can access to inform themselves of the handling challenges that may be encountered. This is the research gap that this thesis will attempt to address.

1.6 Methodology

To achieve the aim, it is necessary to characterise the handling qualities of aircraft that came into use between 1900 and 1950, that is 125 – 75 years ago. Some aircraft from this era exist in museums and a few survive today in a flyable condition. For most of the period under investigation government scientists and academics were investigating all forms of aeronautics and writing reports published by the Advisory Committee for Aeronautics (ACA) and other likeminded organisations but there were no standardised specifications for aircraft handling qualities until after WW2 and as a result little on the subject was 'published' in the accepted academic sense of the word. However, using material in the ACA's Reports and Memorandum (R&M), periodicals and autobiographical texts of pilots it is possible to 'take back bearings' and qualitatively to deduce aspects of stability and controllability to gain an insight into the handling qualities. In addition, more recently, reproductions (either actual flying aircraft or highly sophisticated simulation models of significant pioneer aircraft such as the Wright Flyer) have been produced and assessed.

By analysing the content of historical pilot training syllabi and how they changed over the period it is possible to infer what the state of pilot knowledge was at the time and whether, with current understanding, there were significant flaws in these earlier training methods. It is also possible to deduce something of the characteristics of the aircraft from the methods that were being taught at the time.

1.6.1 Contemporaneous pilot accounts and training methods

To learn to fly an aircraft a trainee pilot must gain the skills necessary to accomplish the task given the characteristics of the aircraft in question. A typical trainee pilot of the period would not be familiar with degree-level flight mechanics and stereotypically, was more likely to be at home on horseback than in a lecture theatre. Moreover, early military pilots were seen as entirely expendable, so there would have seemed little point in taking a great deal of time in educating them to a high level of flight mechanics understanding when the pilot's primary job was to fight and maybe die in the process. While this approach is understandable from a military perspective in the early days, it had unintended consequences in that when such pilots fly the aircraft, they do not analyse its responses with a 'critical' eye – their job is to 'cope' and make the best of the aircraft provided to them. Following the 1918 Armistice, when surviving war pilots were engaged as (untrained) test pilots by manufacturers their opinions on aircraft qualities were strongly influenced by their operational experience which was not necessarily compatible with best practice in peacetime.

Due to the relative paucity of data on handling qualities and associated stability and control requirements before WW2 it is not possible to determine these characteristics directly from scientific papers or airworthiness codes, but it is possible to deduce some characteristics by examining the pilot training methods over the period of interest. This line of investigation is discussed in Chapter 2.

1.6.2 Aspects of stability and control showing evolution

'The ability of an airplane to meet many of the handling-qualities requirements may be estimated quite accurately simply from the dimensions of the airplane.' (Phillips, 1948)

To investigate how aspects of stability and control are influenced by the layout and relative dimensions of aircraft and their component parts the author is indebted to The Shuttleworth Collection for access to its aircraft which together compromise a unique cross-section of aircraft types in use during the period of

interest of this study. The author has been able to take detailed dimensions for inclusion in the analysis described in Chapter 3.

The detailed dimensions have been used to estimate⁴ characteristics of the aircraft in the longitudinal, directional and lateral axes by using long-established generic equations for the parameter of interest. These calculations are carried out in Excel which enables the results of each calculation to be compared with others in the group and differences or similarities displayed for analysis and discussion,

Appendix C contains images and brief descriptions of the aircraft types in the study group. Since most of the aircraft selected for this study are of British design and were built between 1910 and 1950, all published data are in imperial units. For this reason, the calculations in this study have used imperial units to avoid errors of conversion.

1.6.3 Post WW2 certification requirements versus pre-WW2 handling qualities.

The deficiencies of earlier aircraft may be illustrated when compared with current certification specifications (CS) (formerly known as airworthiness requirements) which have been drawn up based on the huge amount of research and development which took place towards the end of and following WW2. In the past each nation developed their own versions for the aircraft they constructed, and these were amended as knowledge was gained through experience. This process resulted in a prescriptive set of requirements which served the industry well for many decades. However, in recent times they have been revised to assist innovation as new technologies emerge, so the most recent amendment of the CS is of a generic nature. This development is unhelpful when attempting to determine whether a particular vintage aircraft is compliant or not so, for the purpose of this study, the earlier prescriptive style of the CS has been used. (Certification Specifications CS-23 Amendment 4, 2015) In Chapter 4 the CS

⁴ It is stressed that the stability and control derivatives presented throughout this study are estimated values derived from aircraft geometry only and must not be taken as authoritative.

provide the benchmark against which the flying characteristics of the vintage aircraft in this study are assessed and illustrative examples are included.

1.6.4 Providing guidance to modern pilots of vintage aircraft

The findings of the investigations above are used to develop guidance to modern pilots flying vintage aircraft. The intention is to inform, avoid repetition of earlier misconceptions and encourage the modern pilot to mitigate risk by being adequately prepared for the deficiencies that might affect the aircraft they fly.

2 QUALITATIVE DATA

2.1 Analysis of contemporaneous pilot accounts

The first research objective was to investigate the handling qualities of early aircraft by analysing and interpreting contemporaneous reports and accounts written by pilots and researchers. It should be recognized that during the period covered by this study aircraft accidents were commonplace. In the pre-WW1 era accidents were expected whenever aircraft flew, the attitude was much the same during WW1 particularly during pilot training. In the 1920s' and 30's the accident rate remained high many being due to loss of control or stall/spin at low height.

Although these accounts often suggest widespread misconceptions it is possible to deduce that, by modern standards, there were significant deficiencies in stability and/or control of aircraft in use in these earlier aircraft which had to be compensated for – although the pilot was probably unaware of the actual underlying cause. Not only did the pilot have to manage such things as instability in one or more axes and perhaps inadequate control power the pilot may have had to compensate for the cross-coupling effects of the rotary engine as it imposed its precession related torques to the aircraft which seriously degraded its handling qualities. These precession effects arise when a torque is applied to a spinning mass such as a gyroscope, rotary engine, or propeller, the output of this torque being displaced through ninety degrees in the direction of rotation. When the aircraft yaws the engine/propeller precession will cause an uncommanded and unexpected pitch, and when the aircraft pitches, the engine/propeller precession will cause an uncommanded and unexpected yaw. Nose mounted rotary engines revolved clockwise when viewed from rear and in the rotary engine era pilots initiated turns by using the rudder to yaw the aircraft in the desired direction – assuming a right yaw the precession effect causes the aircraft to pitch down; a left yaw causes a pitch up. Subsequently the aircraft may

or may not be banked into the turn. In the case of a flat⁵ turn the precession pitch will remain throughout the yawing turn requiring the pilot to counter with an elevator input. In the case of a banked turn, it can be shown that the gyro will experience a combination of pitch and yaw as a function of the bank angle. At shallow bank angles the pitch will predominate requiring a corrective elevator input similar to the flat turn whereas at steep bank angles the yaw effect will predominate requiring a corrective rudder input from the pilot. This will require left rudder irrespective of the direction of turn and thus feels very counter-intuitive when making steeply banked turns to the right.

In this section the author has taken quotations from published works by early aviation protagonists. Their engineering understanding of flight physics ranges from total ignorance to informed guesswork and it is necessary to imagine what the writer was describing and how it appeared to him at the time but interpret that observation using current knowledge. Following its title, the quotation is shown in italics and is referenced. This researcher's interpretation follows each quotation.

2.1.1 Description of a characteristic of the Maurice Farman Shorthorn training aircraft.

“A cambered lifting tailplane was the second design fault. It carried part of the Shorthorn's weight in flight, but it provided less fore and aft stability than a non-lifting stabiliser and lift from it could automatically increase the steepness of a dive and retard recovery to level flight – another possible cause of accidents...”.....“So it is probable that some, perhaps most, of the unfortunately too numerous fatal accidents during Shorthorn

⁵ The flat (or skidding) turn was a method of turning an aircraft and was widespread in Europe before WW1. It entailed using the rudder to yaw the aircraft around the turn (in the same way the rudder of a boat is used), if the aircraft then tended to roll the lateral control system was used to prevent that and maintain wings level. Thus, the aircraft was skidding around the turn, perhaps with the lateral control applied in the opposite sense to the rudder (crossed controls). This technique created sideslip and associated drag which robbed the aircraft of performance. If the pilot allowed the speed to reduce and the angle of attack to increase, then when the aircraft stalled it was set up to enter a spin. Entering a spin in those early days was likely to end in disaster because pilots knew nothing of spinning or how to recover.

flying training were contributed to by ignorance of its inherent design effects” (Macmillan, 1929, p. 16)

A significant number of early aircraft had so called ‘lifting tailplanes’ recognisable by marked camber on the upper surface of the fixed horizontal stabiliser. This configuration was probably chosen to maximise lift and because early aircraft were virtually single airspeed machines due to the low power engines available. However, if the airspeed increased from the ‘ideal’ the aircraft pitched nose down and if that cycle continued the elevator may not have had the control power to recover from the ensuing dive. The reverse is also conceivable wherein too low an airspeed would cause a pitch up which, if not checked promptly, would overcome the available nose-down elevator power. Such aircraft are usually longitudinally unstable but can be flown satisfactorily within their limited speed range provided the time constant of the divergence is within the capacity of the pilot.

2.1.2 The Roe IV (Avro Triplane) used for training at the Avro Flying School at Brooklands 1919-1911

‘Needless to say, it was broken many times as on October 10, 1910, when in the words of an onlooker “a pupil rose unsteadily and after 225 yards slowly sideslipped into the sewage farm, completely smashing the starboard mainplane”.Pixton, practising figure eights at 200 feet on November 8 for his Royal Aero Club certificate, sideslipped Roe IV into the ground, where it caught fire and suffered extensive damage.....It continued to suffer at the hands of trainees such as F. Conway Jenkins, Gordon Bell, R.C. Kemp and Lt W.D. Beatty, until the last mentioned slipped in and badly wrecked it on February 14, 1911.’ Jackson, p. (1990, p. 16)

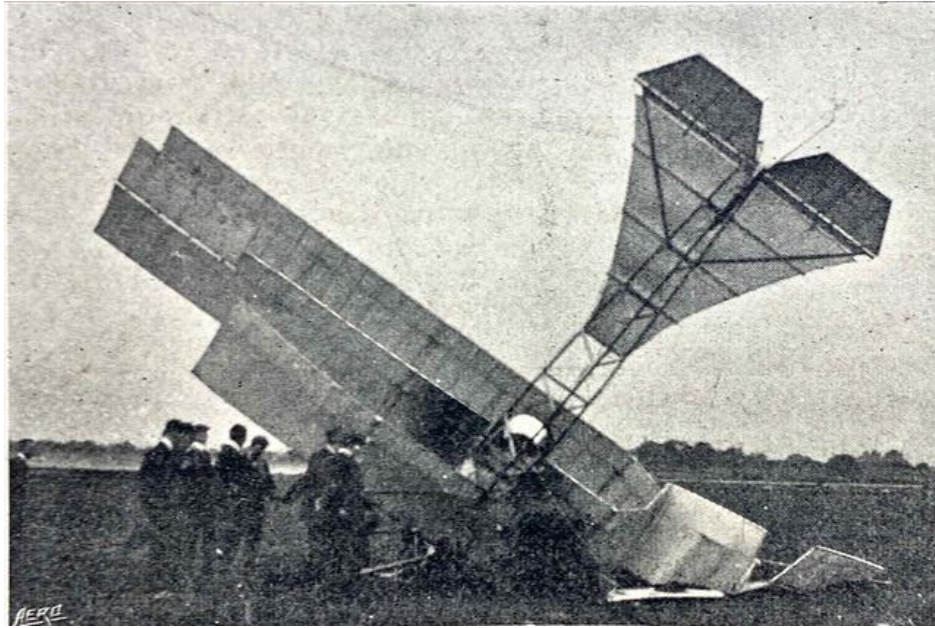


Figure 2-1 - The Roe IV following a sideslip accident (The Aero 1910)

Although this citation is a report rather than a first-hand account it is worthy of inclusion because of the mention of three accidents all attributed to sideslipping into the ground. The group of aircraft investigated in this study includes a reproduction of the Roe IV. The configuration of the aircraft results in an uncommon combination of lateral and directional stability and control characteristics which can result in apparently uncontrollable sideslipping if the pilot ‘over-uses’ the rudder. These characteristics are discussed in more detail in Chapter 3. Pre-WW1 pilots were advised to ‘rudder in’ if they found themselves in a sideslip when turning. This is the correct recovery action **provided** that the pilot has correctly diagnosed the situation – but if the aircraft has stalled or very close to the stall – ‘ruddering in’ will likely result in a fatal spin.

2.1.3 The Morane Parasol and its ‘balanced elevator’.

“None of the Moranes had any [fixed] tailplane. Most aeroplanes have a fixed tailplane with a movable flap on the back of it - the elevator.But the Morane contented itself with the elevator, the movable flap, only and this elevator was a balanced elevator - that is, it carried some surface ahead of its fulcrum. The technicalities really don’t matter: the result was that the elevator was as sensitive as a gold balance; the least

movement stood you on your head on your tail. You couldn't leave the machine to its own devices for a moment; you had to fly it every second you were in the air. The other controls, just to make it more difficult, were practically non-existent. There was a rudder, too small to get you around quickly and ailerons which were so inefficient that sometimes, if you got a bump under one wing taking off, it was literally seconds before you can get the machine on an even keel again.” (Lewis, 1969, pp. 43–44)

This account illustrates just how poor the handling qualities were at the time c1916. Here was an aircraft which had no horizontal stabiliser to provide longitudinal static stability and pitch rate damping, instead it had a so-called balanced elevator meaning a surface with a good proportion of the area ahead of the hinge line to reduce the force needed to deflect it. It is very difficult to get this arrangement correct and nowadays such a system would probably include a mass balance and perhaps a spring and/or an anti-servo tab to give adequate handling qualities. In the case of the Morane if the pilot released the control the elevator would fully deflect either up or down which could be disastrous. Furthermore, the rudder and aileron power are reported as inadequate. Such a combination of deficiencies would be uncertifiable today because survival hangs on a high level of pilot skill to control the machine, and this control is entirely dependent on the link between the pilot's inceptor and the control surface because the pilot is the active stabiliser.

2.1.4 The lack of stability and the essential requirement for uncut control wires.

“One chance bullet from the ground might cut a thin wire, put the machine out of control, and send us, perfectly whole, plunging to a crash we were powerless to prevent”. (Lewis, 1969, p. 50)

“His observer did what he could; but in the first burst the Hun put a bullet through the rudder controls of the Moraine. The machine immediately went into a spin.” (Lewis, 1969, p. 109)

The two observations from Lewis above illustrate that continued controlled flight was entirely dependent on the control wires because of the absence of static stability. Lewis goes on:

“I think I've said enough for the reader, whether he knows anything about flying or not, to realise that the Moraine really was a death trap, thoroughly dangerous to fly, needing the greatest care and skill, the lightest hands and the most accurate judgement to land. Subsequently I flew every machine used by the Air Force during the war they were all child's play after the Morane. (Lewis, 1969, p. 44)

Lewis rightly points out that this aircraft ‘was a death trap’ but interestingly goes on to say that having mastered it he found every subsequent aircraft easy by comparison. It is possible to extrapolate from this remark to the effect that pilot trainers should not be made ‘too’ easy to fly because early experience of a challenging machine can build in superior skills for the rest of the pilot’s flying career. As always there must be a balance – if the trainers are too challenging the students crash them – if the trainers are too easy the qualified pilots crash their operational types.

2.1.5 An illustration of the advantage of longitudinal static stability in the Royal Aircraft Factory SE5a.

“One morning before the rest of us had gone out on patrol we saw him [Albert Ball] coming in rather clumsily to land. He was not a stunt pilot but flew very safely and accurately, so that, watching him, we could not understand his awkward floating landing. But when he taxied up to the sheds, we saw his elevators were flapping loose - controls had been completely shot away. He had flown back from the lines and made his landing entirely by winding his adjustable tail up and down.” (Lewis, 1969, pp. 122–123)

This account illustrates that, in contrast to the Morane described earlier, the SE5a had sufficient static longitudinal stability and enough control through the adjustable tailplane to survive an elevator control cable failure.

2.1.6 An illustration of the advantage of lateral stability of the SE5a after control malfunction

“Whilst on patrol at 17,000 ft I observed an E.A. two-seater about 12,000 ft beneath me. I dived at about 200 m.p.h. for 6000 ft with the engine throttle right back.

Suddenly the machine gave terrific vibration, whilst I was attacking E.A. I pulled out of the dive by winding back wheel a few notches, and turned west on the rudder, being unable to use aileron control. I flew slowly west back to an aerodrome and found the following breakages in machine.

R.H. Top Plane – rear spar broken at aileron joint.

R.H. Lower Plane - front and rear spars split up centre.

L.H. Top Plane - front and rear spars split up centre.

L.H. Lower Plane - apparently OK” (Napier, 1918)

This is a report from Captain I.P.R. Napier, officer commanding A flight of 40 Squadron in April 1918 supplied to the author by David Napier, son of the reporter. In this event Captain Napier had encountered wing flutter when diving on an enemy aircraft (E.A.). The flutter seriously damaged the wings rendering the ailerons ineffective, but he was able to control the bank angle and turn the aircraft by using rudder because the SE5a was designed with sufficient dihedral to provide rolling moment due to sideslip.

2.1.7 In contrast to the stable SE5a, its contemporary the Sopwith Camel lacked stability.

“The [Sopwith] Camel was a buzzing hornet. A wild thing burning the air like raw spirit fires the throat. This fierce little beast answered readily to intelligent handling but was utterly remorseless against brutal or ignorant treatment. Possessed of a sensitive elevator control she reacted swiftly to slight fore and aft movement. I spun her and she fell earthwards in a mad whirl.Her fuselage was short. She was tail heavy, so that one had to press the stick forward in normal flight because there was no tailplane

adjustment. Her rudder was too small. The gyroscopic action of the rotary engine in her light wooden-and-wire framework forced her nose down in a right-hand turn; once this began the rudder could not bring the nose up again. To make a swift right-hand turn without losing height one had to apply left rudder the instant the manoeuvre began and push on full rudder before full bank. Then the Camel turned very fast, far more swiftly than to the left. But let the ham-handed or inexperienced pilot pull the stick just a little too far back while turning all out and the [Sopwith] Camel would flick quickly into a spin which was the pitfall of many a novice and, could be a death trap at low heights.” (Macmillan, 1929, pp. 117–118)

The characteristics of the Camel voiced in dramatic prose, but this is not an exaggeration as described below. (Penrose, 1969, pp. 376–377)

“Even more worrying were Camel crashes through spinning for the SE5a was comparatively immune when flown under similar circumstances. Camels were usually rigged tail heavy with full tank and were longitudinally unstable like the DH-6. This was accentuated when the lighter Le Rhone was substituted for a Clerget, or guns and ammunition were removed. Usually, a continuous forward pressure of some 14 lb was required on the control column when in normal horizontal flight; any relaxation ended in a stall, and so did engine failure unless the pilot instantly dived the machine.

In the course of evidence on the machine’s behaviour most pilots drew attention to the necessity of applying full left rudder in a steeply banked right turn. Torque and slipstream produced unsymmetrical settings of aileron and rudder, but not effects dependent on rate of turn to any great extent, the gyroscopic couple alone being capable of that. Propeller and engine revolved clockwise, viewed from the pilot’s seat, so when the aeroplane was turning right the gyroscopic couple put the nose down, countered by top, that is left, rudder and back elevator. Analysis showed that the effective couple produced by a given setting of the rudder in a Camel was 40% less than for the SE5a, whereas the gyroscopic couple to

be counteracted was more than twice as great. To make the two machines equally effective would necessitate doubling the Camel's rudder area."

To clarify the above explanation it is important to recognise that the 'gyroscopic couple' described by Penrose arises from the gyroscopic precession of the spinning mass of the combined rotary engine and propeller. If the aircraft yaws (right) the precession will pitch the nose (down) and if the aircraft pitches (up) it will yaw (right). When in the steeply banked right turn described above the right yaw rate will be precessed into a nose down pitching moment and the positive pitch rate will be precessed into right yawing moment. To maintain the nose on the horizon in a steeply banked turn in either direction left rudder is needed to prevent the right yaw caused by the precession of the rotating engine mass. Applying left rudder during a left turn does not feel particularly odd but in a right turn it is unnatural and pilots unfamiliar with such characteristics may not apply sufficient left rudder and in an attempt to stop the nose falling below the horizon, pull back further on the elevator which could easily result in a stall/spin departure.

Penrose's remarks concerning rudder size are apposite because, as found in this study, the Camel has the lowest directional static stability and the second lowest rudder power in the WW1 fighter group. See also para 3.4.1.

2.1.8 An alternative opinion on the Sopwith Camel

"The odd thing is that some of them arrive here with the wind up about Camels, which apparently have a bad name in the training schools in England, through pilots being killed right and left by spinning into the ground. Out here in France none of the old Pup pilots has had any difficulty." (Gould Lee, 2014, p. 206)

This is interesting in two ways. Firstly, it reflects the awful accident rate of the Camel when in the hands of the inept or inexperienced. Secondly it shows that when a pilot has had the right preparation, in this case ample experience of the somewhat easier to fly Sopwith Pup, it is far easier to cope with new aspects of a more challenging type. Here the students who were 'spinning into the ground' had probably flown very sedate machines prior to the first solo in the single seat

Camel, whereas Lee had many hours flying the rotary engine Pup which required more pilot skill. In short, the Pup has served as an 'advanced trainer' for the Camel allowing the pilot to adapt to a sensitive machine and therefore be more capable of adapting further to the undoubtedly tricky Camel.

2.1.9 Summary

From the above it has been possible to identify several significant deficiencies in stability and control characteristics which made some of these machines challenging to fly but also examples of the consequences of control system failure in stable or unstable aircraft.

2.2 Pilot Training - Examples of Instructional Methods

The second research objective was to investigate available pilot training syllabi and methods and how they reflect aircraft handling characteristics.

In this section the way pilot selection and training has evolved over the period of interest is illustrated and discussed. In the early days of military aviation it was thought, not without some justification given the aircraft then in use, that a young man who was 'sporty' and a skilled horseman would be the best candidate pilot. It is probably not a coincidence that many cavalrymen were selected because traditionally the cavalry 'scout' for the army and initially that was the role envisaged for the aeroplane – which were often referred to as scouts. To be able to control an unstable steed while mapping the disposition of the enemy forces was an essential cavalry skill which seemed apposite to military flying, along with a certain lack of imagination!

As will be discussed below pilot training manuals were full of fallacies and half-truths. Why this was so is uncertain but perhaps explained by a desire by the writers 'to keep it simple' and to reduce the time needed to learn the 'theory'. Perhaps also because the manuals were often written by 'instructors' who rarely had any rigorous academic training but nevertheless endeavoured to rationalize an aircraft behaviour or response that they had observed in flight to explain it to their pupils. Academics who understood the real physics do not seem to have

taken the trouble to challenge or correct these misapprehensions because academic-to-pilot dialogue seems to have been vanishingly rare.

2.2.1 An example of training for the Royal Aero Club Pilot's Certificate in October 1915 in a 35hp Caudron with the London & Provincial flying school at Hendon.

"The machine moved forwards but had only travelled a few yards when it began turning to the left. I kicked the rudder bar hard over to the right, but the machine continued turning until it completed a circle. I had been too slow in moving the rudder bar and had also failed to maintain sufficient forward speed.

After a few more trial runs I mastered these faults, and I was now told to taxi the machine to the other side of the aerodrome with the tail off the ground. To do this I had to push the joystick forward, rev up the engine and, as soon as the tail lifted, bring back the stick to a neutral position, keeping the engine revving sufficiently to take the machine across the aerodrome. On reaching there the machine was turned around and in a similar way taxied back to the starting point.

I was soon ready for the second stage in training. It was called 'Straights'. Having got the machine into position I left the switch on and, as we moved forward, pushed the stick against the instrument panel. This raised the tail of the ground and as the machine gathered speed, I gradually pulled the stick towards me until left the ground and I was able and for the first time alone. When at a height of about six feet, carrying out my instructions, I pushed the stick forward to a neutral position so that machine continued in horizontal flight. I moved the rudder bar and stick to left or right to correct any deviation from straight and level flight. Having landed on the opposite side of the aerodrome, I turned around and flew back to the starting point. It felt rather like learning to ride a bike or a horse, liable to lose one's balance and fall at any moment. But with each flight my confidence increased soon I was ready for the third stage which was to fly a half circuit

of the aerodrome, landing on the far side and then returning in a straight flight.

One of the L&P pupils, named Moynihan, crashed when flying this exercise. In making a left hand turn he stalled, and side slipped to the ground from about twenty feet. The machine was rather badly damaged, but Moynihan was unhurt and had already got out of the machine when we arrived on the scene.

Soon I was ready for the fourth and final stage of training, a complete flying circuit of the aerodrome. I took off and, as Irvine had instructed me, climbed to a height of 300 feet. I completed a wide circuit and then approached the aerodrome to land. When immediately above the hangars, I pushed the joystick hard against the instrument panel. The Caudron dived steeply until at about 15 feet above the ground I 'yanked' the stick right back. The machine flattened out and touched down well before it reached the centre of the aerodrome. I have never landed another aeroplane as I landed that Caudron, and it has always seemed to me a very rough way of doing so.

I was now considered capable of taking my 'ticket' so I was never given the chance to fly another practice circuit. I think the flying school owners thought their pupils less of a liability if they entered them for their 'tickets' and got them off their hands as soon as possible.

Soon the day for the test arrived. October 7th started with a calm, dull but clear morning as I walked down to the aerodrome at about seven o'clock. The Caudron stood ready for me outside the hangar. Irvine gave me a final briefing and wished me luck. Then he walked out to the centre of the aerodrome to join the empire there. I took off to fly the first prescribed set of five figures of eight. Having completed them, I glided down and, with discreet use of the engine landed within the required distance of 50 yards from a point near the centre of the aerodrome; so finished the first test. The second, which was exactly the same, was carried out without difficulty. I then ascended for the final 'Volplane' test and climbing to the stipulated

300 feet I switched the engine off and descended (volplaned) to make a landing before switching on again.

The same morning, I was informed that I had been successful and in due course the official certificate, No 1840, arrived from the Royal Aero Club. (Rochford, 1977, pp. 23–26)

Having ‘taken the ticket’ as described above one was considered a fully qualified pilot, but the account shows how rudimentary that qualification was. During the early part of WW1 such a qualification was all that was necessary to become a ‘military’ pilot. Later, additional training on service types was provided but was not standardised; some pilots doing many hours while others were rushed off to the front line as replacements without having attained sufficient piloting skill.

2.2.2 Turning techniques in 1912 as reported by a flying instructor:

‘The most dreaded manoeuvre was the right-hand turn. Pupils really funked doing it. Left-hand turns were easy, but, owing to the gyroscopic action of the Gnome rotary engine in flight, the nose of the aeroplane had a powerful tendency on a right-hand turn to rise into a stalling position. This was the principal peculiarity of the rotary engine-driven aircraft of those days. Given the room, it was fairly easy to make a right-hand turn but in a limited radius it was, to the say the least, very tricky. To make the turn it was necessary first to get the nose well down and then to bank and use plenty of right rudder. It was quite a difficult exercise and needed a good deal of practise and confidence.’.....’I shall never forget the fright I had on my first night flight on a similar machine. Casually glancing behind me I saw what appeared to be a gigantic Catherine wheel. My first thought was that the engine was on fire but I soon realised with relief that the ring of flames was caused by the exhaust gases which are not visible in daytime.’ (Warren Merriam, 1954, p. 55)

A great deal can be deduced from this account. First it is necessary to point out the Gnome referred to is a rotary engine meaning that the crankcase, pistons and propeller all rotate together around a stationary crankshaft which is fixed to the

airframe. Therefore, the rotating engine-propeller combination has significant angular momentum and takes the properties of a gyroscope including precession. Any torque applied to a spinning gyroscope will be translated through ninety degrees in the direction of rotation. The last sentence in the quote tells us that the aircraft was a 'pusher' i.e., the engine fitted behind the wings. In this configuration the Gnome engine rotates anticlockwise when viewed from behind the aircraft. For the nose to 'rise' as reported by Warren Merriam the input must have been in the form of a right rudder input which would attempt to yaw the aircraft (and the engine) to the right but that input to the gyro would be precessed through ninety degrees – causing a nose-up pitch. From this we can deduce that the normal way of turning was to yaw the aircraft using the rudder rather than the current technique of using the lateral control system to roll the aircraft into a banked attitude. This deduction is further supported by the reporter's description of large radius versus small radius right turns. He uses the expression 'given room' meaning that when there was no imperative to make a tight turn, a gentle/slack right turn was 'fairly easy'. Since a slack turn could be made using a small rudder deflection and resulting small yaw rate, only a small precession induced pitch-up would result which was 'fairly easy' to manage. But a sharp right turn was 'quite a difficult exercise' because if a large right rudder input was made with the intention of skidding the aircraft rapidly through the desired right turn, then the yaw rate would be proportionally higher as would the precession induced pitch-up; perhaps so much so that a student may not recognise the danger before a stall occurred.

2.2.3 A comparison of two training aircraft - Avro 504 to Shorthorn.

"I discovered how light and pleasant the Avro was. Flying her after the Shorthorn was like driving a sports car after a truck. Her universally mounted mahogany stick was more convenient than spectacles on a one-way column, her rudder bar neater than pedals for operating her featherweight air balanced rudder." (Macmillan, 1929, p. 30)

The 'featherlight air balanced rudder' refers to the fact that the Avro 504 had no fixed vertical stabilizer but instead had an all-flying rudder a part of which was

ahead of the hinge line to reduce the force needed to deflect it. The issue with such an arrangement is that while giving light and effective control it may not provide controls-free directional static stability. If the pilot is not skilled or is perhaps injured and unable to restrain the rudder bar the rudder may fully deflect causing the aircraft to enter a sideslip and then become uncontrollable particularly at low airspeed when the ailerons are less effective.

2.2.4 The ‘inversion of controls theory’ 1916.

“Evidently the instructor wanted to show me vertical turns. I knew the theory of it: Over forty-five degrees the rudder becomes the elevator and the elevator the rudder.” (Lewis, 1969, p. 26)

This remark sums up one of the persistent myths pedaled during WW1 pilot training and for some time afterwards. While it seems to make sense at some level its flaw is that it is rooted in the Earth Axes instead of the Body Axes in which the effect of each primary control is unchanging.

“So primitive was the instruction of 1915 and early 1916, that I was never taught how to turn an aeroplane vertically, nor anything even of the principle of reversal of controls, which is the principle applied to this evolution.” (Balfour, 1933, p. 45)

This pilot also talks of the mythical ‘principle of reversal of controls’ in steep turns and evidently remained a believer two decades later when this was written.

2.2.5 A comment on ‘inherent stability’

“When you put on rudder to turn she's supposed to take up the correct bank herself - that's what they mean by ‘inherently stable’. Don't you believe it. Get her banked correctly on your bubble otherwise you'll turn flat and chase your tail. Spin I mean.” (Lewis, 1969, p. 38)

Inherent stability was the holy grail for some aircraft designers of the period particularly among the ‘pioneers’ from pre-WW1 days. Although it could be applied to longitudinal stability the emphasis here is lateral/directional. The theory being that the rudder was for turning the aircraft i.e. changing direction. When the

rudder is displaced the aircraft yaws in the desired direction and sideslip is created and, provided that the aircraft has adequate dihedral effect, that sideslip will cause a rolling moment thereby rolling the aircraft into a banked attitude. It was believed that an inherently stable aircraft would automatically take up almost the perfect bank angle for the rate of turn commanded by the rudder and only minor adjustments to the bank angle would be needed to centre the bubble in the inclinometer or cross-level. This was a fallacy.

2.2.6 An account of a fatal accident caused by stalling the aircraft when turning.

“We saw him almost soar off the ground and expected to gain knowledge by watching him perform in the gusty half-gale. After a brief flight up wind, he came hurtling back flying parallel to the hangars of the east airfield. When he reached the last one, he made a steep right-hand turn into wind at about 100 feet up, evidently with the intention of landing. But he stalled in the turn. The Bullet dived and hit the ground before he could recover. He was killed almost at our feet.

The official verdict was that he overbanked too near the ground. I theorised about his crash and decided that he stalled because he made a geometric half circle in relation to the ground instead of the terrestrially elongated curve that would have described a true half circle in relation to the air flow. I concluded that when near the ground and turning one must fly by the air flow and never by geometric ground patterns”. (Macmillan, 1929, pp. 36–37)

This was a very insightful analysis of a stall/spin accident by the young Macmillan. The aircraft was a Morane Bullet – a highly wing-loaded monoplane at a time when most contemporary aircraft were lightly wing-loaded biplanes.

2.2.7 Analysis of the development of WW1 pilot training

From the quotations above it is possible to deduce that flying instruction was somewhat haphazard and frequently misleading. In the early years of WW1 instructors were not trained to teach but often were pilots who were ‘resting’ from

the front. Their motivation was personal survival, and they did not want to give learners the opportunity to kill them when the enemy had not been able to thus far. This attitude towards the student pilots, often referred to as 'Huns' to reflect the threat they posed to the 'instructor's' continued existence, was that the sooner the instructor could get out of the aircraft and send the student solo the safer the instructor felt. This approach severely limited the effectiveness of the training and resulted in many student accidents.

This system changed when a visionary called Smith-Barry, who had served as a pilot on the western front, submitted a paper proposing a structured method of flying instruction. Smith-Barry was allowed to establish a 'Special School of Flying' around the end of 1916 at Gosport. His system relied on using properly trained instructors who were suited to the role, along with standardised training aircraft (in this case the Avro 504K) and a syllabus of exercises to be taught in a certain sequence. The Central Flying School (CFS) was in existence before this but subsequently Smith-Barry's Special School of Flying morphed into and became the CFS – a school established primarily for the training of flying instructors. Although his original training syllabus has changed over the years, the principles that he established remain the essence of the CFS instructional method to the present day.

2.2.8 Using an adjustable tailplane on a Sopwith 1½ Strutter.

"Unlike the Avro the Sopwith had an adjustable tailplane, the angle of which the pilot could alter by turning a hand wheel on the right side of his cockpit, thus permitting solo flight from the front seat without ballast in the rear. The wheel had to be correctly set before take-off. It was also another detail to remember when coming down to land, for the wheel had to be wound back to reset the tailplane for the correct gliding speed."
(Macmillan, 1929, p. 38)

This paragraph gives some insight into the way pilots viewed adjustable tailplanes. In the first sentence he describes that the tailplane adjusts to cater for differing centres of gravity as the disposable load is varied. In the last sentence he introduces the idea of setting the adjustable tailplane to glide at low airspeed.

In the second case it is likely that the tailplane had to be 'wound back' (i.e., leading edge down) to give the elevator control authority to flare the aircraft to a three-point landing attitude – if so then this was a controllability issue rather than a trimming issue. Few single seat aircraft were equipped with adjustable tailplanes since their range of possible centres of gravity was less and many were longitudinally unstable or neutrally stable and, in such aircraft, it was rarely if ever 'in trim' in the hands-off sense.

2.2.9 Rolling a Bristol Fighter using the rudder.

'During the dive one has to manoeuvre the aircraft so that the gun sights come "on" the target and then let go a stream of bullets at it. It seems an age, as one's nerves are tee'd up, but really it is all over in a few seconds. When you think you have gone low enough you pull up out of the dive and are pressed hard in your seat, and as you shoot up the earth seems to recede as though some giant hand had snatched it away from under you. Hard rudder, down goes one plane, and you are round and ready to begin again.' (Keith, 1930, p. 263)

This was written around 1930 and describes target practice using the fixed forward firing machine gun in a Bristol F2b. In the final sentence it is clear that to roll the aircraft into the next dive the rudder is being used as the roll control not aileron as would be the norm for post-WW2 trained pilots. The ability of the rudder to make the aircraft roll arises from rolling moment due to sideslip (dihedral effect) and rolling moment due to yaw rate, and the effectiveness of this method was often greater than the rolling moment available from the ailerons. In addition, it avoided the adverse yaw that would result from the use of the primitive flap type ailerons that equipped most WW1 aircraft like the Bristol F2b.

2.2.10 An example of misunderstanding of stalling.

'If he allows the airspeed of the machine to drop below the point where sufficient air is dealt with by the planes in a given time to maintain the machine in flight – i.e., he allows machine to stall - he will lose control, and only regain it when the airspeed has again been increased by diving to a

point when the air dealt within a given time is sufficient to maintain the machine in flight.....He should then immediately put the nose of his machine down to increase the air speed and so regain control.'
(McMinnies, 1918)

It is clear from the above that the writer thinks that it is a lack of airspeed that causes a wing to stall – a popular misconception held to this day by many pilots. A wing stalls when its angle of attack reaches the critical angle and airflow separation occurs – this can occur irrespective of airspeed. The obsession with the stall being airspeed related can be explained perhaps by recognising that early aircraft had very limited performance so stalling usually happened in unaccelerated flight and so seemed to occur always at the same low airspeed. A separate reason is that from before WW1 aircraft were fitted with some form of airspeed indicator whereas reliable angle of attack indicators were not introduced until well after WW2 and then only in military aircraft. Therefore, the instructor felt obliged to use the airspeed indicator as the primary means of avoiding stalling. It is now recognised that irrespective of the indicated airspeed, only reducing the angle of attack with the elevator (or stabilator) will allow the airflow to re-attach and thus take the wing back to an un-stalled flow regime.

2.2.11 How to fly a medium turn in 1918.

'Both the rudder and warp, or the control lever, [stick] are then moved gently and simultaneously in the direction in which it is desired to turn, the right foot being pressed on the rudder to turn right, and the control lever moved to the right to pull up the left wing. The machine will bank gently and come round quite easily. Once the correct amount of bank is on, the lever [stick] can be centred. When the turn is completed the rudder and bank are taken off again, by moving the lever [stick] in the opposite direction, following up with opposite rudder and then moving the control and rudder to their neutral positions.' (McMinnies, 1918))

This instruction shows that the rudder is to be held deflected into the turn for its duration. This 'requirement' to maintain the rudder deflection throughout the turn suggests that the aircraft concerned is deficient in directional static (weathercock)

stability as in, when 'completing' the turn the rudder 'follows-up' the aileron because whilst the aircraft still has some bank into the left turn some left rudder will be required to prevent it from 'slipping in'. The rudder can only be reset to the datum position when the wings are level. In modern aircraft with adequate directional stability, the rudder is not used to roll or yaw the aircraft during a turn but only to minimise any adverse yaw produced while the ailerons are deflected. During the turn there should be no requirement for rudder except to counter yawing moments arising from the engine/propeller. Therefore, when making a medium turn there is a difference in the 'timing' of the rudder inputs between ancient and modern techniques. Pilots who have trained on aircraft with strong weathercock stability may misuse the rudder when flying a vintage aircraft with deficient directional stability.

2.2.12 When making turns with greater angles of bank, the then widely held belief in the 'inversion of controls' during 'vertical' turns is discussed.

'Now consider what happens when the machine is made to execute a vertical bank turn and is on its left side relative to the horizon. If left rudder is held on when the machine is on its side in the turn it will cause the nose to approach the left wing but it will cause the nose to drop below the horizon.' (McMinnies, 1918)

The phrase 'If the rudder is held on' is there because as described above, that was the standard technique for gentle/medium turns.

'Next take the action of the elevator when the machine is on its side in a steep turn. If the control lever [stick] be pulled back it will cause the nose of the machine to try to approach the tail, but as the machine is on its side in relationship to the horizon, this backwards movement of the stick will simply speed up the turn and make the machine turn more quickly. So that if the nose of the machine is still compared with the horizon, it is found that on a vertical bank the nose is trimmed above or below the horizon by the use of the rudder and the machine made to turn by the use of the control lever which operates the elevator. At turns of 45° the rudder acts half as

rudder and half as elevator and the elevator acts half as rudder and half as elevator. At lesser angles the elevator is more elevator than rudder and the rudder more rudder than elevator, when the nose of the machine is compared with the horizon, whilst at steeper angles of turn the elevator becomes more and more the rudder and the rudder more and more the elevator.’ (McMinnies, 1918)

This is mostly nonsense of course. Now there is a better understanding of the flight mechanics of turning flight and such a technique is not only unnecessary in a modern aircraft, but its use would also be inefficient at best.

Mc Minnies was the not only one advocating these techniques, but very similar explanations are also given elsewhere, in the reference below, they are expanded to cover the effects a rotary engine when a [tractor] aircraft is turned.

‘..... when a machine is turning to the right, it is necessary to hold up the nose by putting on a little left rudder, and similarly that left rudder must also be kept on [during] a left-hand turn, to hold the nose down. This is a simple and practical demonstration of a fact which is generally a great puzzle for a beginner: namely that when turning steeply either to the right or left on a rotary machine in each case when in the turn some left rudder must be used.’ (Hobbs, 1919)

This illustrates that, in addition to the deficiencies in stability and control already alluded to, the student pilot had to compensate for the somewhat capricious cross-coupling effects of the rotary engine.

Given that many flying instructors in the inter-war period were either Great War veterans, or had been trained by one, it would appear that the approach to flying training remained rooted in this style for many years.

2.2.13 How to turn 1920

‘I will now deal with turning in normal flight. Suppose you wish to turn to port. To produce this turn you have got to supply a force towards the centre of the circle you are going to turn about, and at the same time produce a

couple to point the nose of the aeroplane always in the direction of flight as you go round the curve. You supply the force by banking or tilting the aeroplane with the port wing down and the starboard wing up; under these conditions the air force on the wings, instead of acting vertically upwards, is inclined towards the centre of the turn, thus drawing the aeroplane out of the straight path to a curved path. At the same time a couple is required on the aeroplane to swing it so that it points continually round the curve; this couple you supply by ruddering to port. For any rate of turn, that is to say, amount of bank, there is only one correct amount of rudder to give; if you give more you point the nose too much round and skid outwards; if you give less, you slip inwards. For steep banks, that is sharp turns, your elevator has to be called into play, and it takes some time to learn to co-ordinate the movements of your rudder, ailerons and elevator correctly.’ (Hill, 1921)

Hill was a well-respected WW1 veteran and test pilot. In this extract he talks of ‘ruddering to port’ being necessary and that, for any given rate of turn (or bank) there is only one correct amount of rudder. [He is not specific amount whether this ‘amount of rudder’ is a control deflection or a force.] This is how turning was done at that time and taken at face value; it means that the aircraft he is describing lacks the directional static stability needed to yaw into the turn naturally without the pilot making a significant into-turn rudder input which would not be necessary in a well-designed modern aircraft.

2.2.14 How turning was taught in 1939

Twenty years after McMinnies and Hobbs little had changed as can be found by reference to a diagram in The Complete Flying Course by Harben (1939) with researcher’s comments added in text boxes.

TURNING LEFT**MEDIUM TURNS (with engine)**

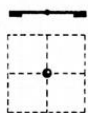
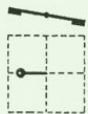
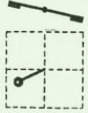
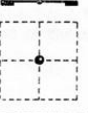
ACTION		EFFECT	REMARKS
THE MEDIUM TURN Approximately a bank of 45°. For demonstration purposes it is divided into three phases : (1) Going in ; (2) staying in ; (3) coming out. (1) GOING IN Set tail trim to fly level. Look round.			These steps are analogous to 'modern' technique
Bank and rudder together. If anything, lead with bank.		Aeroplane takes bank and nose tends to drop.	However, rudder is not centred once in the turn as it would be using the 'modern' technique.
Gentle back pressure on stick.		Keeps nose on horizon and helps the turning.	
Continue back pressure on stick until required bank is reached.		The aeroplane is now turning, but the bank is increasing.	 Bank increases on its own, because the outer wing travelling faster on the outside of the circle obtains more lift.
Hold off bank sufficiently to keep it constant.		Rudder deflection is maintained during 'Staying In' to prevent the aircraft 'slipping in'. This is indicative of inadequate directional static stability. Note also the aileron is deflected opposite to the direction of the turn to prevent 'rolling moment due to sideslip' and 'rolling moment due to yaw rate' from increasing the angle of bank i.e., 'holding off bank'	
(2) STAYING IN Maintain these conditions.			
(3) COMING OUT Select an object on the horizon. Opposite bank and rudder. Stick forward.			
Centralise when level and heading towards your object.			

Figure 2-2 - Medium turn technique 1939

Figure 2-2 shows the rudder deflected throughout a turn with a need for out-of-turn stick deflection or, in the vernacular, 'holding off bank'. The need to hold into-

turn rudder throughout the turn to avoid 'slipping in' is indicative of low directional static stability. So, this suggests that some aircraft being used for training in 1939 suffered from similar stability and control deficiencies as those in 1919. Therefore, it can be posited that there had been little improvement in the lateral/directional handling qualities of training aircraft during the 1919-1939 period.

2.2.15 An indication that the handling qualities of training aircraft were transitioning

The RAF's 1942 Instructors Handbook of Elementary Flying Training (AP1732a, 1942, p. 43) describes some considerations when teaching medium turns as follows:

"It has been explained in the considerations of earlier exercises that if an aeroplane is banked it will automatically yaw owing to its natural stability. This fact helps considerably the modern conception, because it means that no application of rudder is necessary to yaw the aeroplane [in the direction of the turn]. The rudder need only be applied if there is an appreciable slip. In some types the slip may be appreciable and in such instances rudder should be used, but only so much as is necessary to correct the slip."

This extract is of interest because it comes from a time of transition between old fashioned biplanes with low directional static stability, which tend to slip inwards when banked, and the newer (monoplane) types with stronger directional static stability which do not – 'the modern conception'. The author of this manual has been careful to include methods for both types because his readers may be called upon to instruct on either sort as they were in service contemporaneously.

2.2.16 How turning is taught after WW2.

Post WW2 the instructor's manuals had changed as exemplified by (Campbell, 1994). By now the technique for entering, maintaining and recovery from turns had evolved to:

'Turn Entry – Coordinated use of aileron to achieve a bank angle of 30°. Rudder to maintain balance (cross reference to balance indicator). Elevators to adjust pitch attitude to give constant altitude.

Maintain – Bank [angle] – adjusted and maintained by the use of ailerons. Balance - adjusted and maintained by use of the rudder. Pitch attitude – adjusted and maintained by use of the elevators.

Recovery to straight flight and level flight - Coordinated use of aileron to roll wings level. Rudder to maintain balance (cross reference to balance indicator). Elevators to adjust pitch attitude to maintain a constant altitude.'
(Campbell, 1994, pp. 9–24)

This technique is used to the present day. It recognises and does not compromise the underlying flight mechanics. It also illustrates that the associated post-WW2 training aircraft has adequate directional static stability such that rudder deflection is not needed to maintain a turn but is used only as necessary to maintain balance [i.e., no resultant side force]. It also illustrates that the aircraft has adequate longitudinal stability in that it expects a 'back pressure' to be required and requires that the elevator adjusts the pitch attitude to correct minor height excursions rather than the rudder being used to adjust the nose attitude with respect to the horizon as in the earlier manuals. [There was no mention of a requirement to maintain height during the turn in the earlier manuals simply because the altimeters then in use lacked sufficient resolution.]

2.2.17 Roll due to yaw rate

The difference in airspeed over inside and outside wings during a turn arises because as the aircraft yaws around the turn the outer wing must move faster than the inside wing and, assuming both wings are at the same lift coefficient in a level turn, then the more rapid the yaw rate the greater the imbalance of lift across the span causing the bank angle to increase over time. This is known as rolling moment due to yaw rate and the accepted first approximation is that it approximates to one quarter to one sixth of the lift coefficient. This effect may have been noticeable in pre-WW1 aircraft which flew slowly (and at high C_L). At

the low rates of turn associated with normal banked turns of say 3-6°/sec, and at lower lift coefficients achievable in later aircraft with a larger speed range, this effect is marginal.

2.2.18 Rolling moment during climbing and descending turns

Climbing and descending turns are treated differently over the period. Climbing turns are barely mentioned in (McMinnies, 1918) probably because the training aircraft he addressed had insufficient excess power to accomplish them. In AP-129 (AP129, 1926, pp. 30–31) the tendency for the bank angle to increase during climbing turns but not during descending turns is explained by the difference in helix angle altering the angle of attack on inner and outer wings – the effect being to cause an into-turn roll in climbing turns and the opposite in descending turns. This effect is said to be modified by the roll due to rate of turn described in 2.2.17. In a climbing turn these two effects are cumulative, whereas in a descending turn they are of opposite sign. This explanation is also used in (AP1732a, 1942, p. 48).

2.2.19 Bank angle changes during inclined turns.

While the explanations given in the references in paragraph 2.2.18 seem reasonable it is just as likely that what the flying instructor authors of those handbooks were seeing and attempting to explain was the manifestation of the Euler relationship which causes the bank angle to change in inclined turns at a rate proportional to the product of the rate of change of heading ($\dot{\psi}$ in earth axis) and the sine of the pitch angle (θ). This effect is relatively modest at small values of θ but becomes very noticeable as the inclination angle of the turn increases.

Typically, a pilot aims to maintain a constant bank angle during academic turns in which case an out-of-turn input on the lateral control system becomes necessary in climbing turns and an in-to-turn input during descending turns, with the amount of input being proportional to the inclination angle.

Therefore, in the early days of flight when airspeeds were low and rates of turn (yaw) relatively high, the need to 'hold off bank' would arise during the skidded (flat) turns that were 'de rigour'. It is conceivable that legacy knowledge found its way into flying instructor lore and persisted for many years after. The effect during climbing and descending turns remained, albeit at a modest level, in typical academic turns. Little emphasis is placed on these effects in more recent flight instructor manuals which only discuss Rate 1 turns ($3^\circ/\text{sec}$) when climbing or descending. That a modern aircraft requires less pilot attention in this regard is illustrated by there being no mention of 'holding on rudder⁶' or 'holding off bank⁷' during turns in the Flight Instructor Manual by Campbell (1994)

Although some insight can be gained by examining legacy flying training material modern pilots must not assume that the content represents the very best method to fly such vintage aircraft today. As illustrated above they can contain a certain amount of well-intended guesswork, and myth; and techniques which are better avoided.

2.2.20 Summary

In this section the paucity of early pilot training is exposed and some of the legacy flying methods/techniques are shown to be different from those typically used today. The over-reliance on 'inherent stability' and the dominance of the rudder as the way to turn the aircraft being typical examples. The absence of trimming devices meant that for many years pilots accepted the need to apply continuous control forces before the advent of trimmable tailplanes which although intended to provide sufficient control authority for all loading conditions were quickly utilised by pilots as a way of reducing the longitudinal stick force during flight. It is possible to trace the evolution of the methods taught for turning including the mythical

⁶ The term 'holding on rudder' refers to the archaic technique for turning an aircraft in which the pilot attempts to turn the aircraft by rudder alone and holds the rudder deflected throughout the turn, whether the aircraft is banked or not.

⁷ The term 'holding off bank' refers to the archaic technique for turning when the rudder is held deflected for the duration of the turn [see previous footnote] and, rolling moment due to sideslip or rolling moment due to yaw rate or a combination of both causes the bank angle to increase and the pilot prevents this with an 'out of turn' lateral control input.

‘inversion of controls’. Also, an analysis of the explanations of the need to hold off bank during turns suggests that techniques adopted for Pre-WW1 aircraft persisted in manuals and instructor patter, long after their applicability had gone.

3 ANALYSIS OF STABILITY & CONTROL CHARACTERISTICS.

3.1 Preamble

The third objective was to conduct an analysis to estimate open-loop stability and control characteristics of a representative sample of ‘vintage’ aircraft to determine how such characteristics evolved during the first fifty years.

3.1.1 Control Harmony

Harmonisation of control is defined by Stinton (1983) as:

“Controls are said to be well harmonised when forces and deflections and response of the aircraft to them, are such that the pilot is not aware of having to use too much or too little effort. A rule passed down from the Second World War is that, for sweet handling, the aileron: elevator: rudder force needed to produce a common rate of response about each axis should be: A: E: R = 1 : 2 : 4”

This ideal, which is the expectation of pilots trained on modern aircraft, is rarely encountered on vintage aircraft, many of which have low longitudinal static stability and associated pitch sensitivity; the rudder often has the ‘lightest’ control feel, and ailerons the heaviest; thus A: E: R = 4 : 1 : 2 or 4 : 2 : 1 is typical.

When analysing the effect of forces and moments it is important to establish a consistent axis system. In flight mechanics the axis convention is shown in Figure 3-1 from Perkins & Hage (1949)

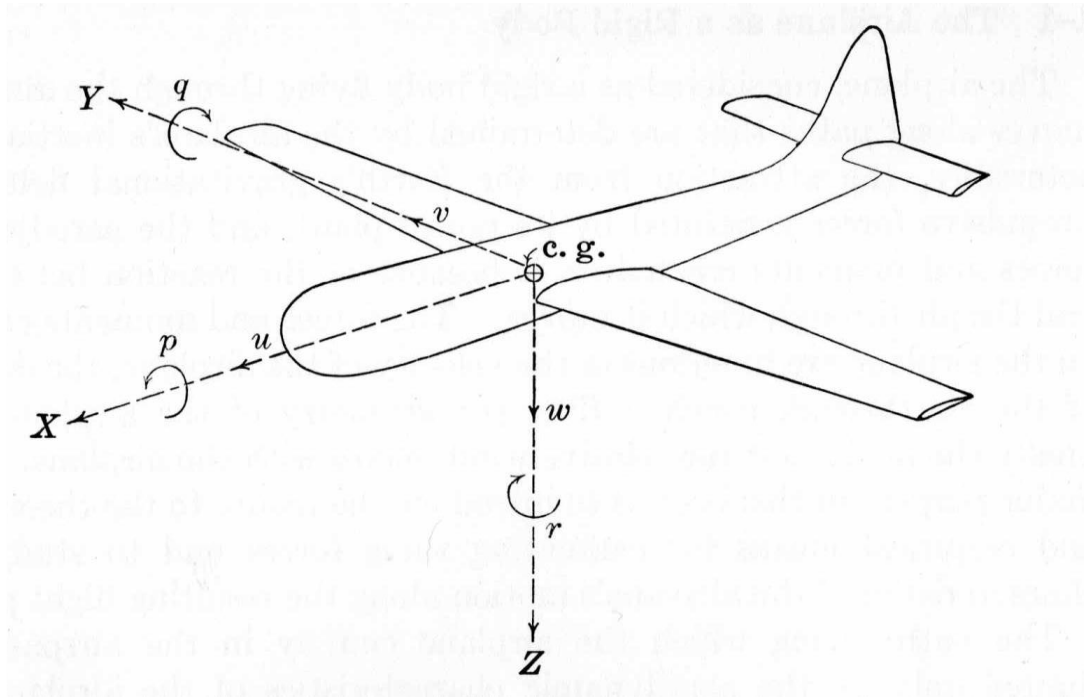


Figure 3-1 – Aircraft Axis System

The arrows on the diagram indicate positive directions.

The forces and moments and the aircraft motion components are shown in Table 3-1.

Table 3-1 – Forces, moments, velocities, and angular rates

AXIS	FORCE ALONG	MOMENT ABOUT	LINEAR VELOCITY	ANGULAR DISPLACEMENT	ANGULAR VELOCITY	INERTIA
X	F_x	L	u	ϕ	p	I_{xx}
Y	F_y	M	v	θ	q	I_{yy}
Z	F_z	N	w	Ψ	r	I_{zz}

The direction of the relative airflow arriving at the aircraft axes is resolved into velocities u , v , w as shown in Table 3-1 but it is often convenient to consider the angular difference between the relative air flow and the applicable aircraft axis as shown in Figure 3.2 where $w/u = \tan \alpha$ (angle of attack) and $v/u = \tan \beta$ (angle of sideslip) in radians. Positive directions shown.

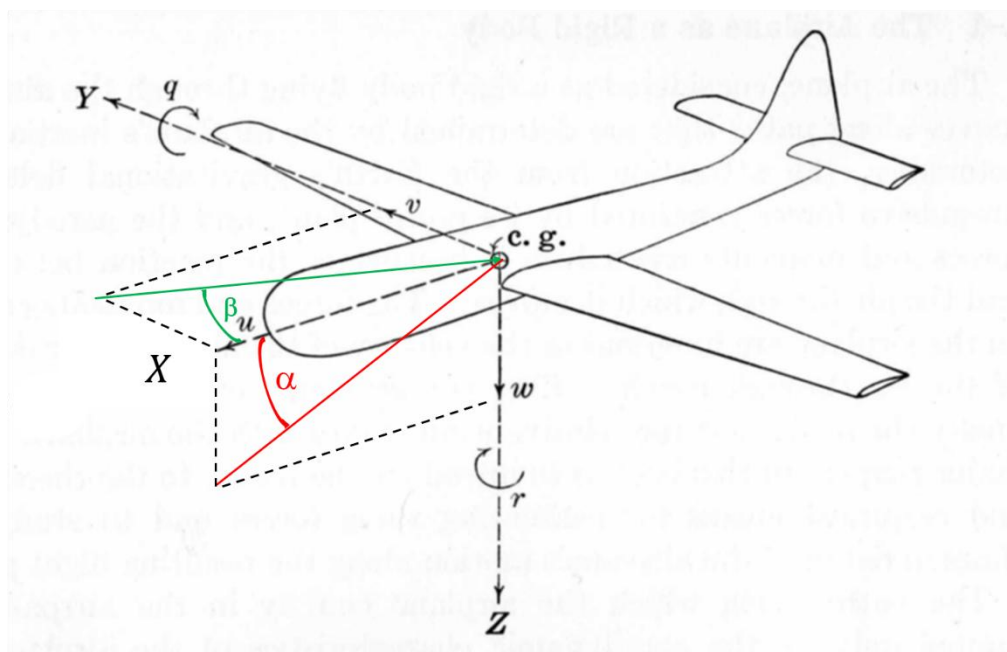


Figure 3-2 – Airflow Directions

Physical dimensions and derived attributes have been collated and incorporated in a spreadsheet to illustrate how the aircraft in this study compared to the design advice from the post WW2 era. These derived longitudinal stability and control characteristics have been calculated for 41 aircraft originating from 1909 to 1950. In addition, five typical light aircraft designed in the 1960s and 1970s were also analysed to compare the characteristics of aircraft certificated with the benefit of the extensive stability and control research fallout from the Second World War. Elements of this data are plotted either, to show the development over time or, the relationship between one parameter and another which may give an insight into how design philosophy adapted to external influences such as pilot feedback, war and/or emerging research data. Equations are introduced and referenced as they are used in the analysis but see Appendix D for a complete list of equations used.

3.2 Longitudinal parameters

Taking moments around the centre of gravity (cg) where lift and drag of wing and tail have been resolved in normal and chordwise forces the equation for longitudinal balance is:

$$M_{cg} = N x_a + C z_a + M_{ac} + M_{Fus} + M_{Nac} + [M_{Pwr}] + [M_{Gyro}] + M_{act} + C_t h_t - N_t l_t \quad (3-1)$$

(Perkins & Hage, 1949, p. 214 Eq. 5-2)

Figure 3-3 shows these terms diagrammatically and illustrates how the angle of attack of the wing links the normal forces and the lift and drag forces.

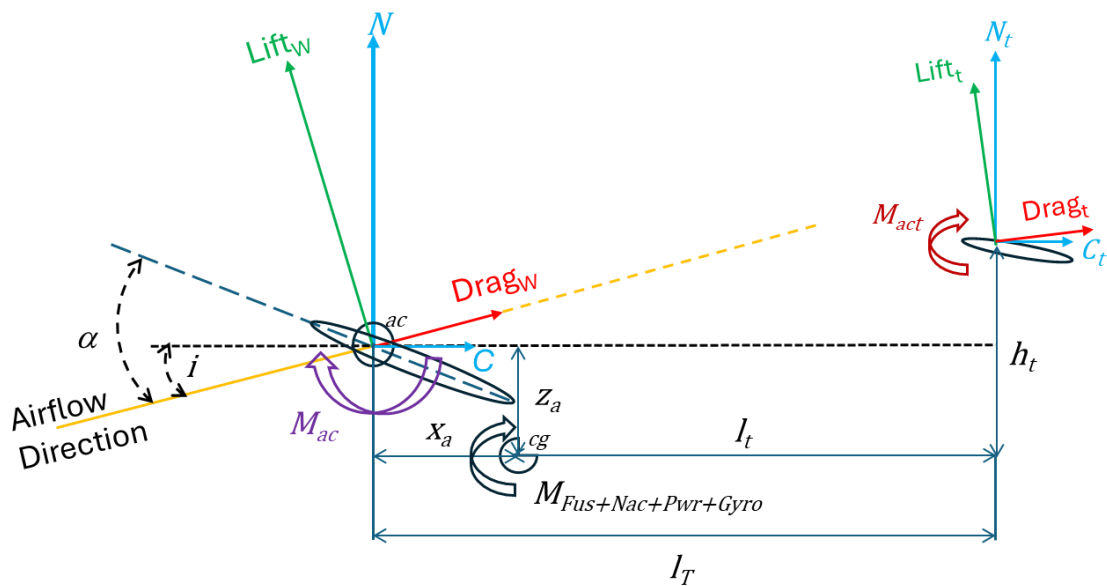


Figure 3-3 – Forces, distances and moments

Where the terms are defined in Table 3-2 below.

Table 3-2 – Forces, distances and moments

N	Force normal to aircraft longitudinal axis	$N = Lift \cos(\alpha - i) + Drag \sin(\alpha - i)$
x_a	Horizontal distance between the cg to the aerodynamic centre (ac) at 25% chord.	
C	Chordwise force, parallel to aircraft longitudinal axis.	$C = Drag \cos(\alpha - i) - Lift \sin(\alpha - i)$
z_a	Vertical distance between the cg to the ac.	
M_{ac}	Pitching moment of the wing.	
M_{Fus}	Pitching moment of the fuselage.	

M_{Nac}	Pitching moment due to the nacelles (usually applicable multi-engine aircraft).
$[M_{Pwr}]$	Pitching moment due to the engine/propeller.
$[M_{Gyro}]$	Pitching moment due to the gyroscopic precession of engine/propeller.
M_{act}	Pitching moment of the tailplane aerofoil.
C_t	Chordwise force of the tailplane.
h_t	Vertical distance between the cg and the ac of the tailplane.
N_t	Normal force of the tailplane
l_t	Horizontal distance between the ac of the wing and the ac of the tailplane.
l_T	Horizontal distance between the aircraft cg and the ac of the tailplane.

In the interest of completeness two terms have been added to the original equation [shown in square brackets]. They are pitching moment due to the effects engine power and the pitching moment that arises through the gyroscopic precession of the spinning engine/propeller combination when the aircraft yaws which is discussed in section 3.5 Cross coupling.

When the sum of the moments in the right-hand side of the equation is zero ($\Sigma M=0$) the aircraft is said to be in equilibrium (or balance) or trimmed⁸ meaning that since there is no net pitching moment there will be no rotation about the y axis.

It is more usual to work in coefficient form so, by dividing through by $qS_w\bar{c}$ where, S_w is the wing area, $\bar{c}$ is the mean aerodynamic chord of the wing, and q is the dynamic pressure which is defined as $\frac{1}{2}\rho V^2$. Then, ignoring minor terms M_{act} and $C_t h_t$, equation 3-1 becomes.

$$C_{M_{cg}} = C_N \frac{x_a}{\bar{c}} + C_C \frac{z_a}{\bar{c}} + C_{Mac} + C_{M_{Fus}} + C_{m_{Nac}} + [C_{m_{Pwr}}] + [C_{m_{Gyro}}] \quad (3-2)$$

$$- C_{N_t} \frac{S_t}{S_w} \frac{l_t}{\bar{c}} \eta_t$$

(Perkins & Hage, 1949, p. 215 Eq. 5-4)

⁸ Trimmed in this context is $\Sigma M=0$ but does not imply that the pilot's inceptor force is zero.

where:

C_N is the coefficient of the wing normal force which is a function of lift coefficient (C_L) and the angle of attack (α).

x_a/c is the horizontal distance between the cg and the wing ac expressed as a fraction of the wing chord,

z_a/c is the vertical distance between the cg and the wing ac expressed as a fraction of the wing chord,

The two terms in square brackets have been added to the original referenced equation as discussed above.

C_{Nt} is the coefficient of the tail normal force which is a function of the lift curve slope of the horizontal tail ($dC_N/d\alpha$)_t or (a_t) and the angle of attack at the tail (α_t).

S_t is the area of the horizontal tail, and

η_t is tail efficiency factor which is the ratio of dynamic pressure at the tail q_t over the dynamic pressure at the wing q_w .

This equation does not infer stability. For stability, an increase in lift coefficient (C_L) must result in a nose down pitching moment so it is necessary to differentiate the trim (balance) equation with respect to C_L (or angle of attack (α)) and for the result to have a negative sign to ensure longitudinal static stability.

Differentiating equation 3-2 with respect to C_L gives

$$\begin{aligned} \frac{dC_M}{dC_L} = & \frac{dC_N}{dC_L} \frac{x_a}{\bar{c}} + \frac{dC_c}{dC_L} \frac{z_a}{\bar{c}} + \frac{dC_{Mac}}{dC_L} + \frac{dC_M}{dC_L} (Fuse) + \frac{dC_M}{dC_L} (Nac) \\ & + \left[\frac{dC_M}{dC_L} (Pwr) \right] + \left[\frac{dC_M}{dC_L} (Gyro) \right] - \frac{dC_{Nt}}{dC_L} \bar{V}_t \eta_t \end{aligned} \quad (3-3)$$

(Perkins & Hage, 1949, p. 216 Eq. 5-5)

The first term is the wing contribution which can be seen to be dependent on the cg position represented by x_a/c . The second term can be neglected for mid-wing aircraft (Since most of the aircraft discussed in this thesis are biplanes in which

the vertical position of the equivalent monoplane chord is usually taken as 4/7 of the gap between upper and lower wings which closely approximates to a mid-wing arrangement.) The third term is zero. (Pitching moment change around the aerodynamic centre being invariant of change of C_L .) The fourth and fifth terms are usually destabilising but will vary depending on fuselage and nacelle arrangement. The two terms in square brackets have been added to the original referenced equation as discussed above.

The final term represents the horizontal tail contribution and comprises three elements. The term dC_{Nt}/dC_L is the ratio of lift curve slope of the tail ($a_t = dC_N/d\alpha_{TAIL}$) and lift curve slope of the wing ($a_w = dC_N/d\alpha_{WING}$) and a correction for downwash of $(1 - d\varepsilon/d\alpha)$, where ε is the downwash angle at the tail and α is the wing angle of attack. So, the final term of equation 3-3 may be rewritten as follows:

$$\left(\frac{dC_M}{dC_L}\right)_{Tail} = -\frac{a_t}{a_w} \bar{V}_t \eta_t \left(1 - \frac{d\varepsilon}{d\alpha}\right) \quad (3-4)$$

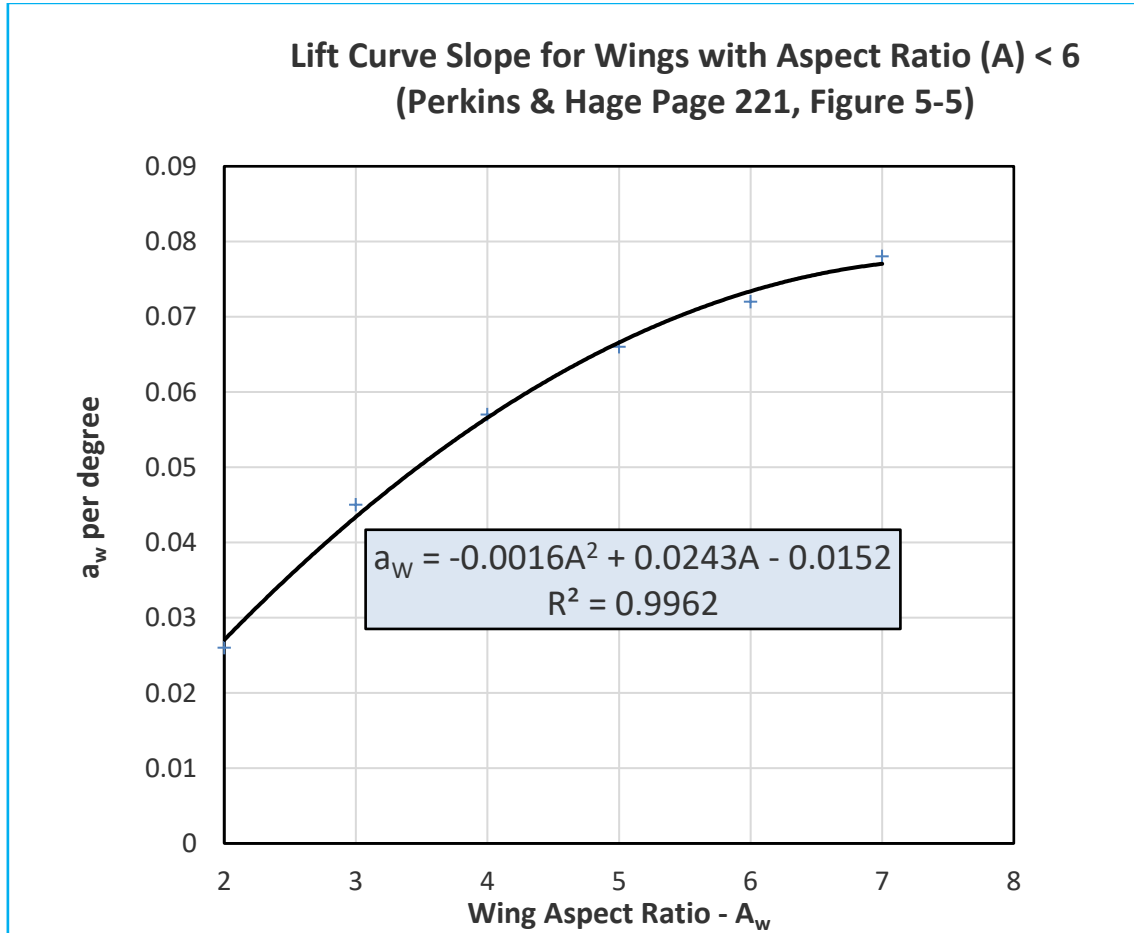
(Perkins & Hage, 1949, p. 220 Eq. 5-19)

Where a_t is the lift curve slope of the horizontal tail, which can be estimated from the aspect ratio of the horizontal tail (A_t) using the empirical formula below.

$$a_t = \frac{\pi A_t}{1 + \sqrt{1 + \left(\frac{A_t}{2}\right)^2}} \quad (3-5)$$

(Seckel, 1964, p. 60 Eq. 5d)

While a_w is the lift curve slope of the wing which can be estimated from the appropriate monoplane or biplane wing aspect ratio (A_w). For $A_w < 6$, a_w was taken from (Perkins & Hage, 1949, p. 221 Figure 5-5); reproduced in Figure 3-4.



The equation of the curve fit in Figure 3-4 is used in the analysis to estimate the lift curve slope for wings with $A_w < 6$.

For $A_w > 6$, a_w can be estimated from one of the following equations:

$$a_w = \frac{2\pi A_w}{(A_w + 2)} \text{ for monoplanes} \quad (3-6)$$

(Stinton, 1983, p. 127 Eq. 4-19a)

Or

$$a_w = \frac{1.65\pi A_w}{(A_w + 2)} \text{ for biplanes} \quad (3-7)$$

(Stinton, 1983, p. 168 Table 4-3, Eq. 4-36)

The average aspect ratio of the aircraft in the study group is 6, with a minimum of 3.3 (Bristol Boxkite 1910) and a maximum of 9.6 (Westland Lysander c 1939).

While it is difficult to determine downwash ε by analysis or measurement, an empirical equation for $d\varepsilon/d\alpha$ is shown in equation 3-8.

$$\frac{d\varepsilon}{d\alpha} = \frac{114.6}{\pi A_W} a_W \quad (3-8)$$

(Perkins & Hage, 1949, p. 222 Eq. 5-23)

Which relates $d\varepsilon/d\alpha$ to wing aspect ratio (A_W) and wing lift curve slope (a_W).

Where:

$$A_W = \frac{b_W^2}{S_W} \text{ for monoplanes} \quad (3-9)$$

And

$$A_W = \frac{(kb_W)^2}{S_W} \text{ for biplanes} \quad (3-10)$$

(Stinton, 1983, p. 158 Table 4-2)

S_W is the reference wing area, b_W is the wingspan and k is Munk's Span Factor. An equation for Munk's Span Factor (k) is shown in equation 3-11.

$$k = \sqrt{\left[1.8 \left(\frac{G}{b_W}\right) + 1\right]} \text{ for biplane} \quad (3-11)$$

(Stinton, 1983, p. 157 Eq. 4-30)

Where G is the gap between the top and bottom wings.

The term η_t in equation 3-4 is the tail efficiency factor, described earlier, and is the ratio of dynamic pressure at the tail compared with that at the wing. The wake from the fuselage and wing reduces tail efficiency (η_t), values varying between around 0.9 down to as low as 0.5. In this analysis, given the designs and layouts of the aircraft considered, a mid-value of 0.75 is assumed for gliding and cruising

flight. The high energy slipstream from a propeller operating at take-off or climb power will likely increase η_t but that is not considered here.

Lastly, the term $\bar{V}_t$ in equation 3-4 is the horizontal tail volume coefficient which is the horizontal tail volume ($S_t^*l_t$) This parameter is relatively easy to determine by making direct measurements on an aircraft or from a scale general arrangement drawing. However, given that such dimensions differ considerably between aircraft it is necessary to convert this into non-dimensional form, by dividing it by the wing volume ($S_w^*\bar{c}_w$). The values of this horizontal tail volume coefficient for different aircraft can then be directly compared.

It is possible to estimate the horizontal tail contribution to longitudinal stability by evaluating equation 3-4, repeated below as 3-12.

$$\left(\frac{dC_M}{dC_L}\right)_{Tail} = -\frac{a_t}{a_w} \bar{V}_t \eta_t \left(1 - \frac{d\varepsilon}{d\alpha}\right) \quad (3-12)$$

Therefore, from parameters derived from measurements taken from an aircraft or estimated from published experimental data, it is possible to estimate many significant parameters which affect the horizontal tail contribution to longitudinal static stability dC_M/dC_L Tail. Taken in isolation, this parameter does not provide everything needed to determine the static stability of the aircraft because no evaluation has been made of the contributions from wing, fuselage and power. However, if the values of dC_M/dC_L Tail are collected for a large set of 'geometrically similar' aircraft, useful comparisons may be made.

Using a similar analysis technique, it is possible to estimate other parameters of interest such as Elevator Control Power ($C_M\delta_E$).using equation 3-13 which shows that the power of the elevator to create or oppose pitching moments is a function of the lift curve slope of the horizontal tail (a_t), the horizontal tail volume coefficient ($\bar{V}_t$), the tail efficiency(η_t), and the elevator effectiveness parameter $d\alpha_t/d\delta_E$ which is known as τ_E .

$$C_M\delta_E = -a_t \bar{V}_t \eta_t \tau_E \quad (3-13)$$

(Perkins & Hage, 1949, p. 250 Eq. 5-72)

Where τ_E is a function of the ratio of elevator area (S_E) to the area of the complete horizontal tail (S_t). The relationship of τ_E to S_E/S_t is from (Perkins & Hage, 1949, p. 250 Figure 5-33).

The referenced data were replotted in Figure 3-5 and the equation of the curve used to estimate τ_E from the calculated value of S_E/S_t for each subject aircraft. In the group of aircraft being assessed most values of S_E/S_t are between 0.4 and 0.6 and the curve fit in that range is acceptable for the purpose of this study.

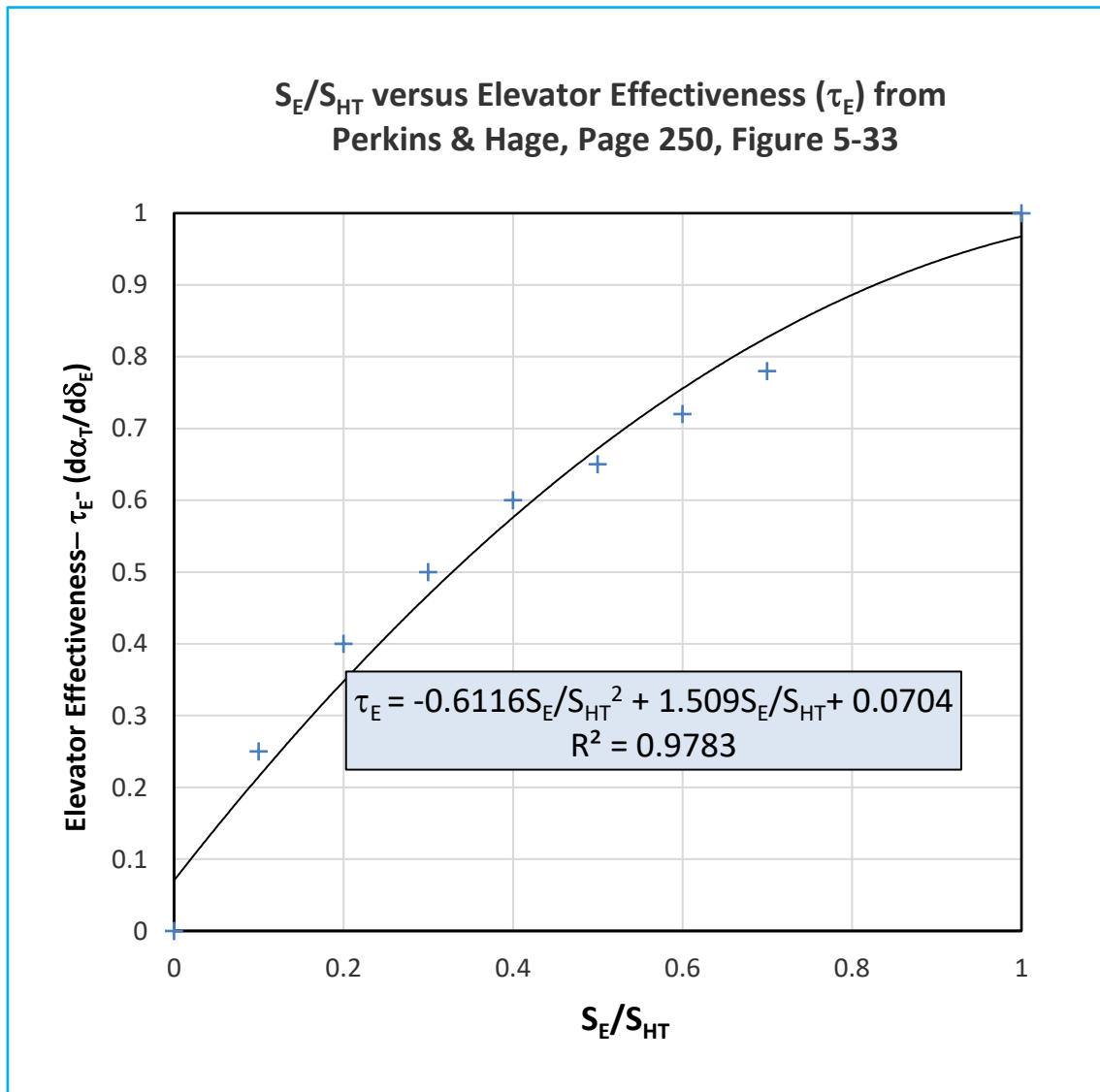


Figure 3-5 - Elevator Effectiveness (τ_E)

The horizontal tail volume coefficient ($\bar{V}_{HT}$) is a major factor in both stability and control being the means by which forces and moments are created from inclinations to the airflow.

In Figure 3-6 the tail volume coefficient ($\bar{V}_{HT}$) for each subject aircraft is shown versus its year of manufacture along with recommended upper and lower boundaries. The subject aircraft have been placed into evolutionary groups namely, Pre-World War One, World War One fighters, and Lympe Trials (1923-24 light aircraft competition entrants). These three groups are subdivided into biplanes, annotated (B) and monoplanes, annotated (M). Then, there are biplanes from 1920-30, civilian monoplanes from 1930-40, military monoplanes 1930-40, and monoplanes from the immediate post-WW2 era 1946-52 fitted with tail-wheel landing gear, annotated (TLG). Finally, as a 'control', there are a selection of equivalent light aircraft from 1960-70 fitted with nose-wheel landing gear, annotated (NLG).

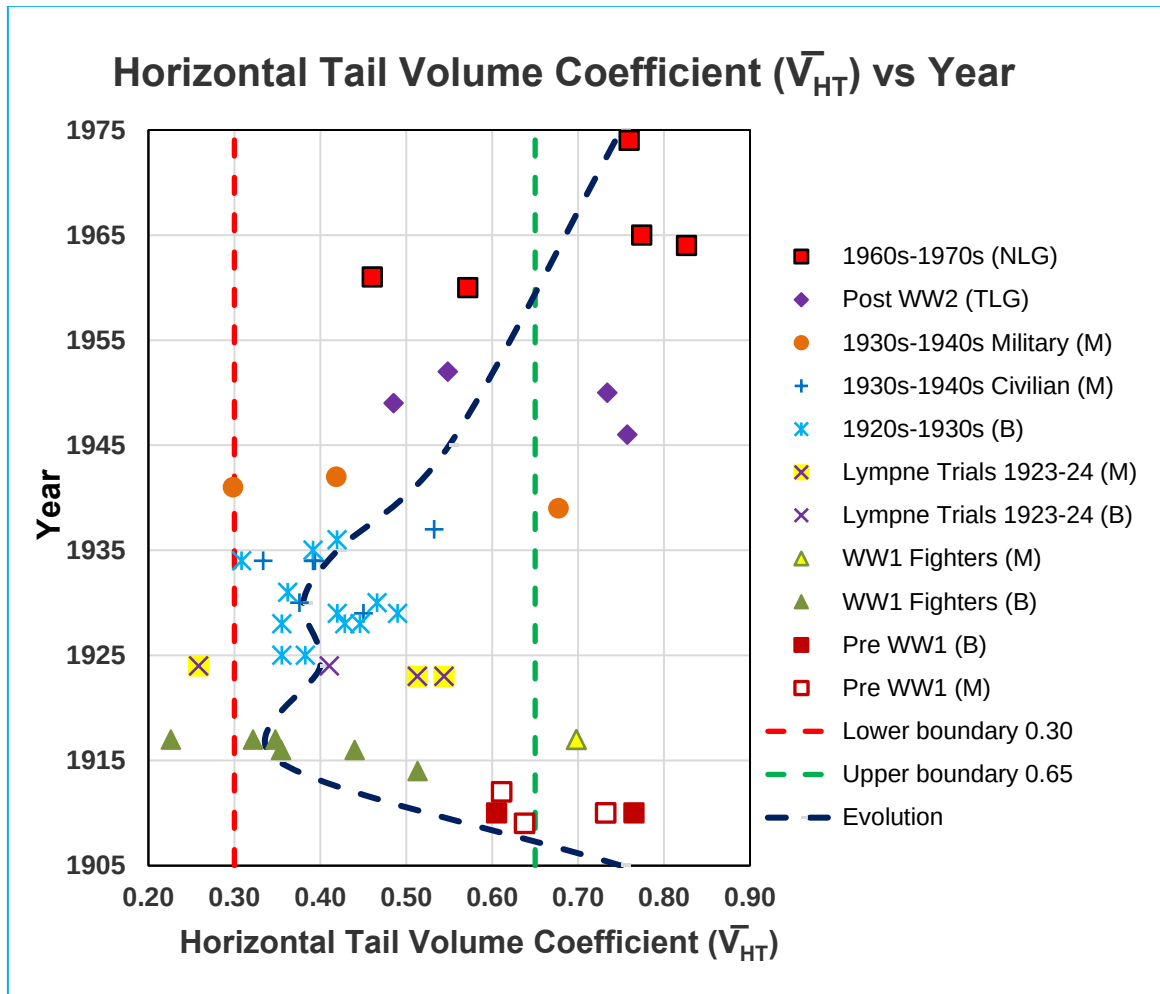


Figure 3-6 - Horizontal Tail Volume Coefficient vs Year.

The recommended design boundaries for $\bar{V}_{HT}$, 0.3 to 0.65 are from ‘The Design of the Aeroplane. (Stinton, 1983, p. 395 Table 11-1)

This plot shows that values of $\bar{V}_{HT}$ were relatively high in the very early days, fell considerably during WW1, increased again for the Lympne Trials aircraft, before falling again during the mid-1920s to mid-1930s – increasing again in the post WW2 era and further into the 1960s.

However, it must be remembered that over the period 1905-1955 stalling speeds increased by two to three times and maximum level speeds by an order of magnitude.

Recall that in converting to coefficient form, equation 3-1 was divided through by $\bar{q}_w S_w C_w$ which is the product of the dynamic pressure at the wing ($\bar{q}_w$) multiplied

by the wing volume. It follows that to determine actual forces and moments the reverse operation is required. The value of q is derived from equation 3-14.

$$q = \frac{1}{2} \rho V^2 \quad (3-14)$$

Where ρ is air density and V is airspeed. Given the V^2 term it follows that at very low airspeeds and therefore low q , a greater value of tail volume coefficient may be needed, and conversely at high airspeeds and high values of q , lower levels of tail volume may be sufficient. One interpretation of the data shown in Figure 3-6 is that, given that $\bar{q}$ is a function of V^2 , any aircraft with a very low stalling speed and a very small speed range will require larger surfaces to achieve the stabilising or control response necessary for safe flight than an aircraft operating at higher $\bar{q}$. Thus, the Pre-WW1 types and the ultra-light/ultra-low power Lympe Trials aircraft have relatively larger tail volume coefficients. In WW1 agility in combat became a highly desirable characteristic for fighters (then referred to as scouts) and, given the level of understanding of most aircraft manufacturers at that time, agility seemed to be related to small tail volumes and ‘relaxed’ static stability or even significant longitudinal instability. Later, as airspeeds increased and as the requirement to fly for long periods by sole reference to instruments evolved, the need for a higher level of static stability emerged necessitating greater values of tail volume as can be seen from Figure 3-6 from about 1935 onwards. This can be further illustrated if the horizontal tail volume coefficient is multiplied by the product of $\bar{q}_w$ and tail efficiency factor η_T as shown in Figure 3-7.

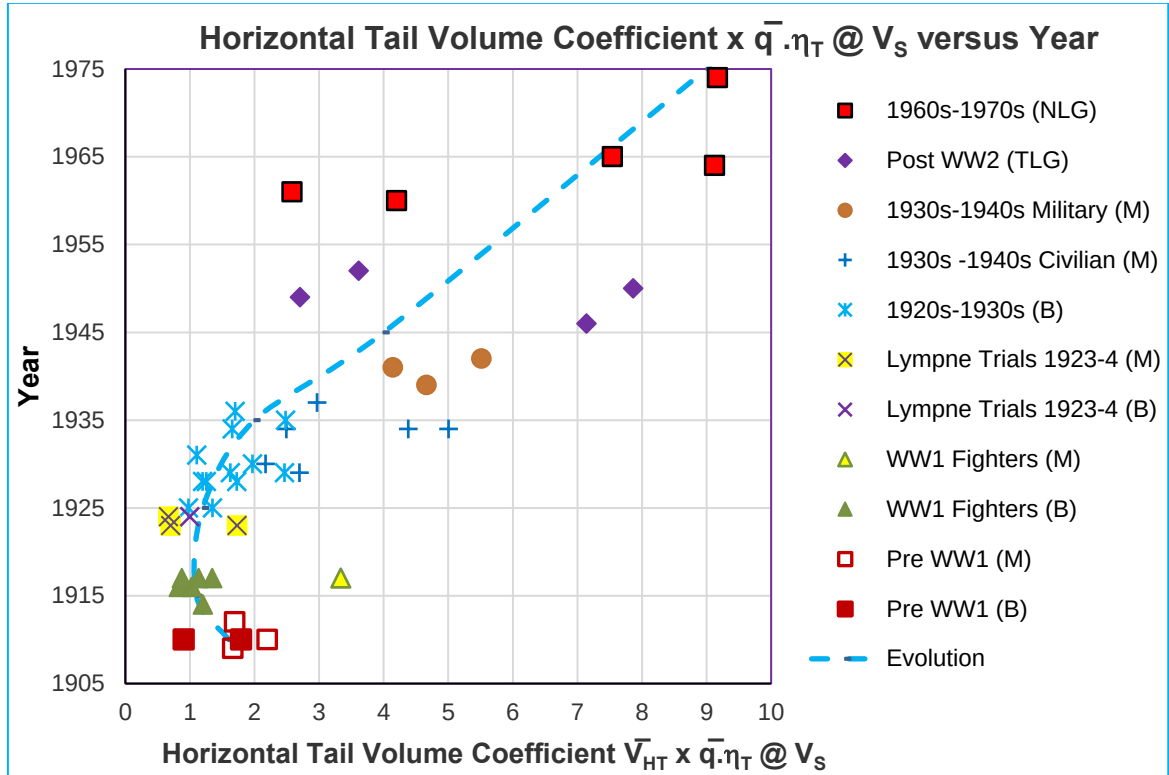


Figure 3-7 - Horizontal Tail Volume Coefficient $\times \bar{q} \cdot \eta_T$ at V_S versus Year

The evolution of parameter $\bar{V}_{HT} \cdot \bar{q} \cdot \eta$ (where the q used is that at the stalling speed V_S) can be seen to reduce from the Pre-WW1 era to WW1 then remain nearly constant until the mid-1930s – thereafter the parameter steadily increases as both tail volumes and stalling speeds increase over time. The effect is even more marked when the q used is at the aircrafts' maximum level flight speed V_H as shown in Figure 3-8.

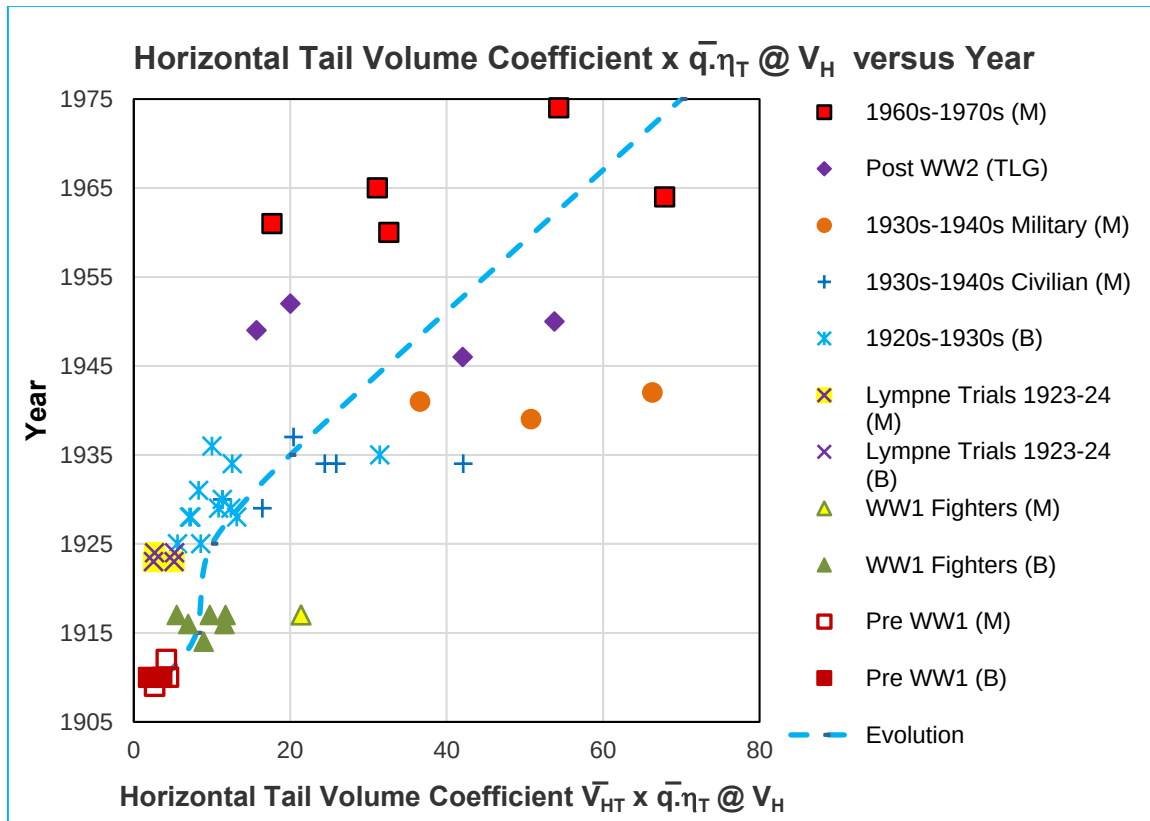


Figure 3-8 - Horizontal Tail Volume Coefficient $\times \bar{q} \cdot \eta$ at V_H versus Year

The WW1 monoplane fighter (Bristol M1c 1917) appears as an outlier at just over 20 units, and this is due in part to a horizontal tail volume being three times greater than its contemporary, the Sopwith Camel (1917), whose score on this figure is 5 units. The significance of this is illustrated in RAE No B.A.251 (1918) which states *'The centre of gravity of [Camel] B2312 having been measured, a rough calculation of its stability was made to discover if any reasonable increase of elevator area would ensure its stability. it is estimated that the present total tail area (23 sq. ft) would have to be about doubled to make it at all satisfactory in this respect. The present ratio of tail to wing area (10:1) is of course abnormally small, and it would seem that radical changes of design are necessary to make this aeroplane stable.'* The Bristol M1c tail to wing area ratio is (4:1) and is known to exhibit strong longitudinal stability whereas the Sopwith Camel is disconcertingly unstable. Another outlier can be seen in 1934, at just over 40 units this is the DH-88 Comet Racer which enjoyed one of the highest maximum level flight speeds at that time of 220 MPH. The three points around 1940 are worthy

of explanation, they are the Hawker Hurricane (fighter) at 36 units, the Westland Lysander (army cooperation) at 50 units and the Vickers Supermarine Spitfire (fighter) at 66 units respectively. Of these the Hurricane has the lowest score due to having the lowest tail volume (the Mark 1 is longitudinally unstable), the Spitfire has 40% greater tail volume than the Hurricane, and has positive but low longitudinal stability, but it is its high maximum level flight speed that earns it the high score. The Lysander is not as fast as the other two, its role required a very low landing speed, and it enjoys a tail volume which is 60% greater than the Spitfire and 225% of the Hurricane. The Lysander is known to exhibit strong longitudinal static stability.

3.2.1 Estimation of the contribution to longitudinal static stability of the complete horizontal tail

The contribution of the complete horizontal tail to longitudinal static stability dC_M/dC_L (*TAIL*) (equation 3-12) was evaluated for each subject aircraft and, assuming that all the other contributions to longitudinal static stability are similar for these subject aircraft, this parameter is indicative of the likely level of stick-fixed longitudinal stability.

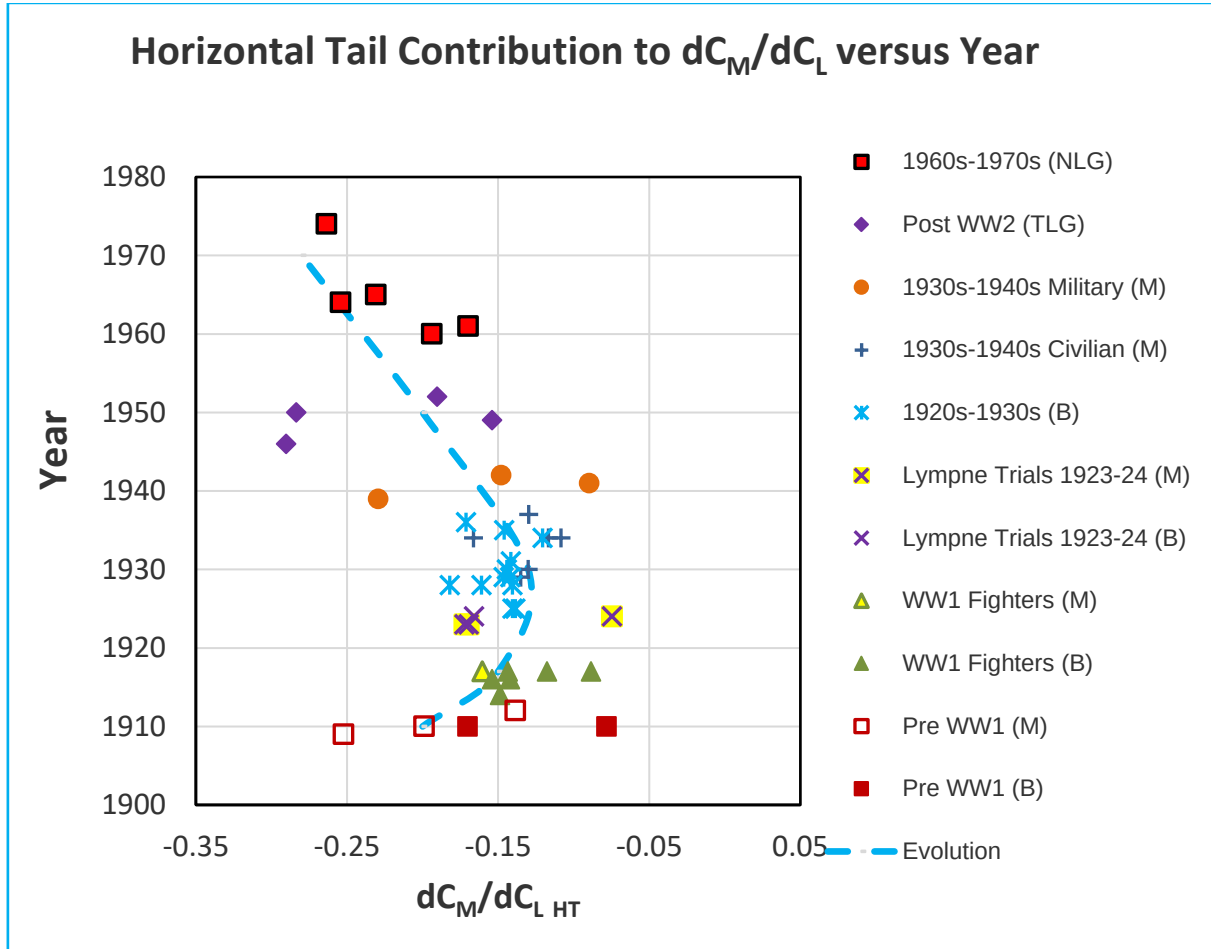


Figure 3-9 - Horizontal Tail Contribution to Longitudinal Static Stability vs Year

In Figure 3-9 the parameter $dC_M/dC_L_{(HT)}$ is plotted against year of manufacture. This shows it at a minimum in the period 1915 to around 1930 after which there was a steady increase through to the 1960s. Other contributions being equal, this parameter is indicative of potential for stick-fixed longitudinal static stability and, while there is insufficient data to discuss stick-free stability with any accuracy, an indication can be gained by repeating the calculation using only the fixed tailplane volume coefficient instead of that for the complete horizontal tail. This typically shows an average reduction of 50% in the magnitude of $dC_M/dC_L_{(TAIL)}$.

3.2.2 Estimation of elevator control power

As shown in equation 3-13 above it is also possible to estimate elevator control power ($dC_M/d\delta_E$) using parameters derived by analysis. Both $dC_M/dC_L_{(TAIL)}$ and $dC_M/d\delta_E$ rely on the product of tail volume coefficient $\bar{V}_{HT}$ and the tail efficiency

factor η_T , while equation 3-13 contains the lift curve slope of the tailplane (a_t) and the elevator effectiveness (τ_E) from Figure 3.5. Therefore, the two parameters, dC_M/dC_L (TAIL) and $dC_M/d\delta_E$ will have similar characteristics and will follow trends in $\bar{V}_{HT}$.

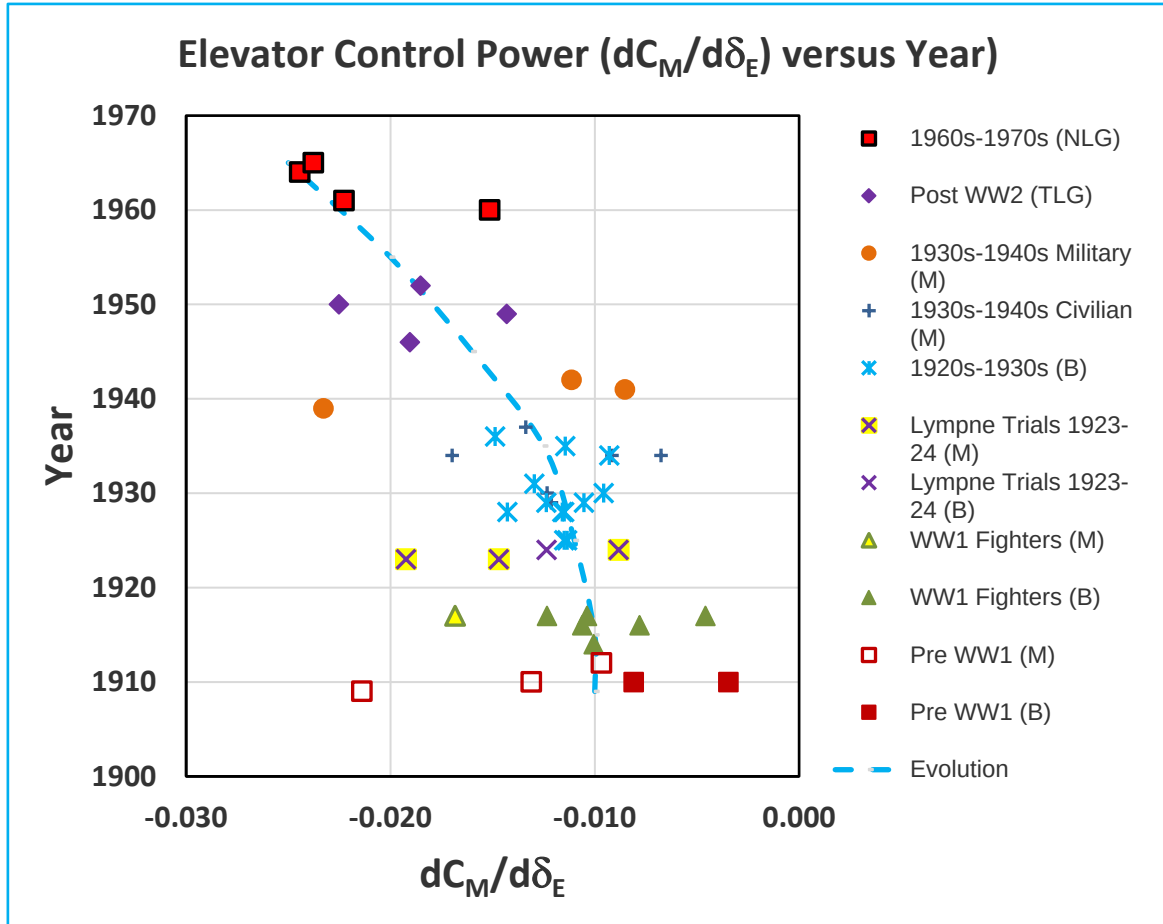


Figure 3-10 - Elevator Control Power vs Year

In Figure 3-10 $dC_M/d\delta_E$ shows a similar trend to that of dC_M/dC_L shown in Figure 3-9, but this is an overly simple relationship and gives a somewhat anomalous result since, for a given aircraft geometry, elevator power appears to increase if dC_M/dC_L is reduced for example if the manoeuvre margin is lower.

Figure 3-11 is a cross plot of $dC_M/d\delta_E$ versus dC_M/dC_L and shows a near linear evolution of steadily increasing static stability and elevator control power. This is true based on the equations used but is probably not what pilots experience as

the complete pitching response is a function of controls free stability and of manoeuvre margin which is not included in this analysis.

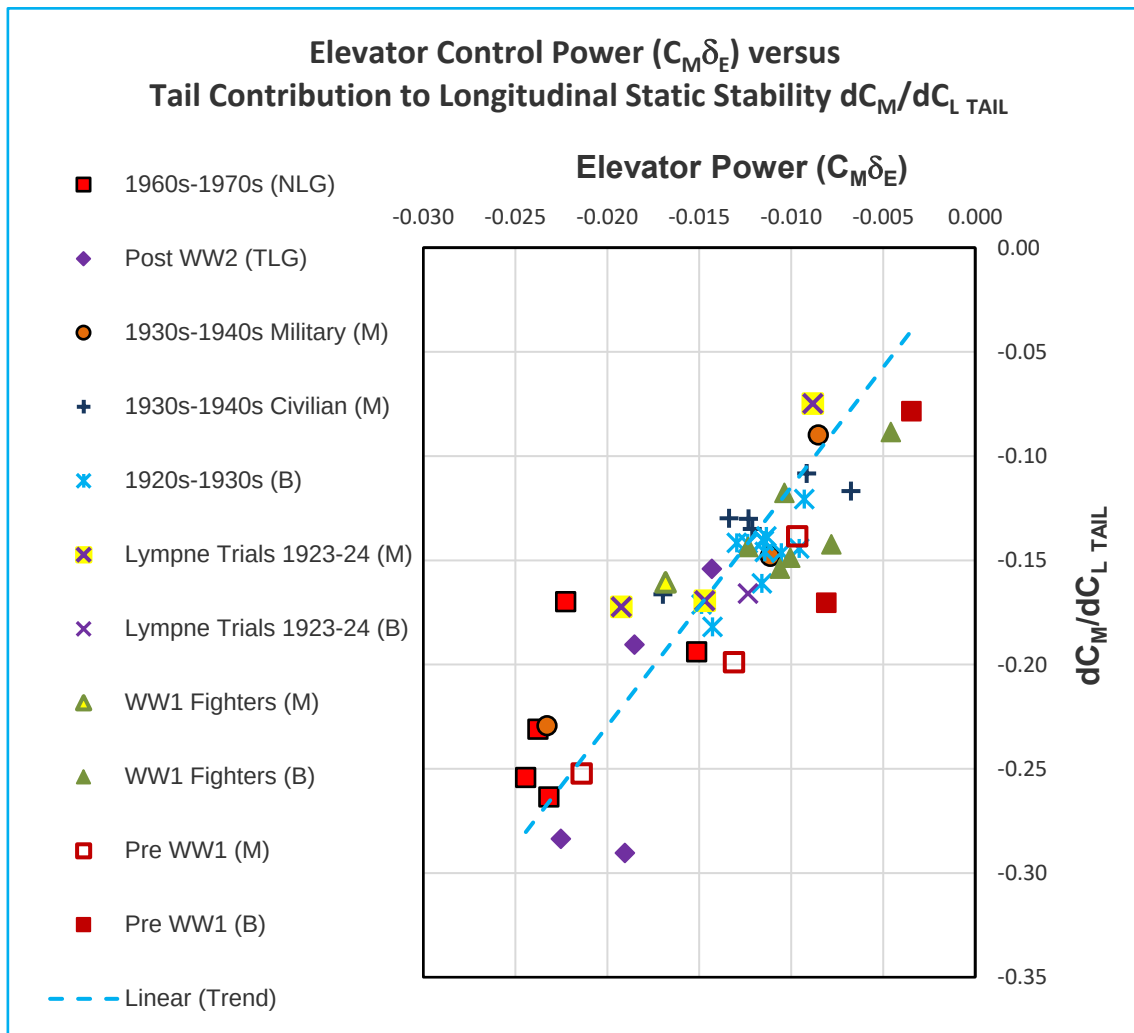


Figure 3-11 - Elevator Power versus Tail Contribution to Longitudinal Static Stability

3.2.3 Estimation of moments of inertia and relative density

Longitudinal handling qualities are also affected by the moment of inertia about the lateral axis (I_{YY}) and pitch damping i.e. pitching moment due to pitch rate (C_{Mq}). Determining moments of inertia accurately for all the aircraft in this study is beyond the scope but given that these aircraft are all of conventional construction and geometry an approximation of moments of inertia has been established 'The Design of the Aeroplane' (Stinton, 1983, p. 487 et seq. Figure 13.14 a, b, c). Stinton's figures are plotted on log:log axes with a straight line fit.

In Figure 3-12 the data extracted has been replotted on linear axes with a 'Power' curve fit so that the equation of the applicable line can be used in the spreadsheet calculations to provide an estimate of the relevant moment of inertia from the aircraft weight. The equations of the curve fits are shown in Figure 3-12.

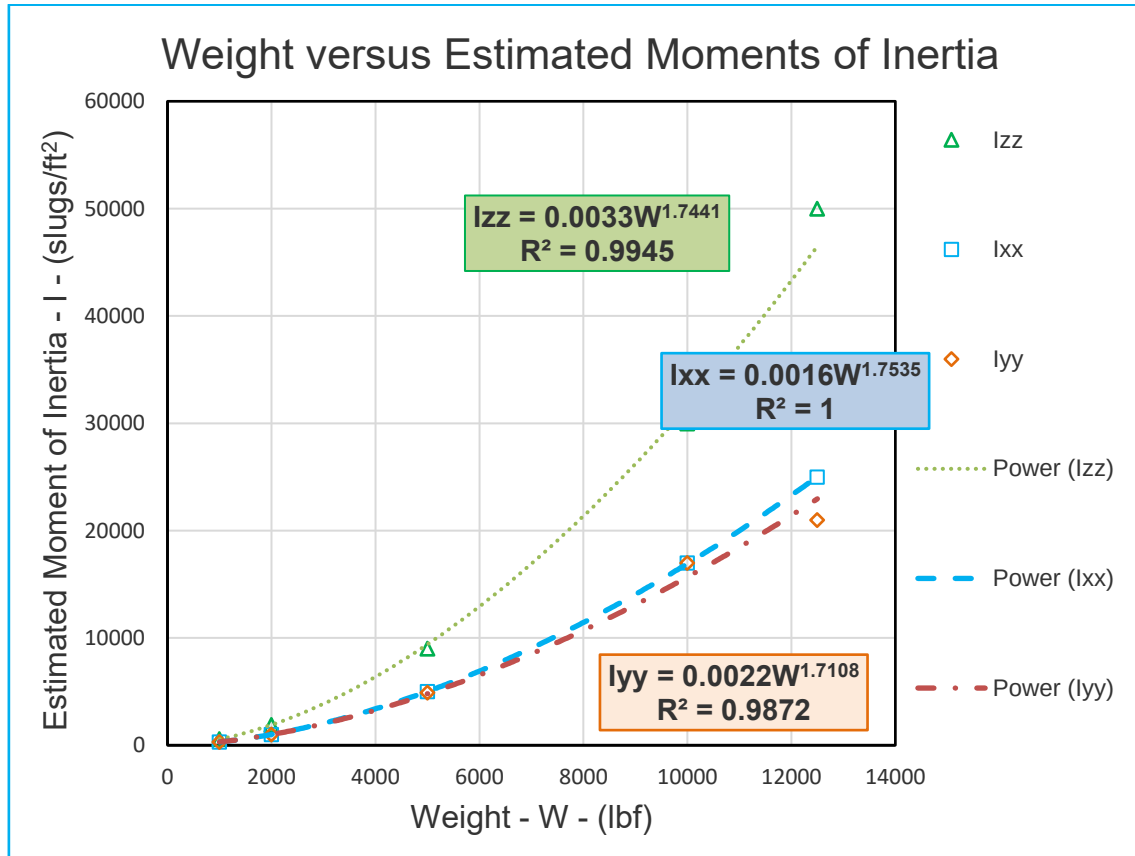


Figure 3-12 - Weight vs Estimated Moments of Inertia

Pitch damping affects manoeuvre stability and the short period pitching oscillation inter alia. An equation for pitch damping is:

$$C_{M_q} = -1.1a_t V_t \eta_t \frac{l_t}{\bar{c}} \frac{1}{\mu} \quad (3-15)$$

(Perkins & Hage, 1949, p. 395 Eq. 10.80)

Where, a_t , V_t , η_t , l_t and $\bar{c}$ are defined earlier. To include the damping effects provided by other parts of the aircraft other than the horizontal tail the 1.1 factor is included. The symbol μ represents the 'airplane relative density factor' which

is the ratio of the aircraft mass to the mass of air of a volume based on aircraft dimensions. An equation for μ was found in NACA TN D-6575 (1971) – equation 3-16.

$$\mu = \frac{m}{\rho S b} \quad (3-16)$$

The relative density is a measure of how ‘mass loaded’ an aircraft is for its size. It can be seen from the equation that C_{Mq} is inversely proportional to μ meaning that the greater the value of μ the lower the pitch damping. Many of the early aircraft in this study are very light structures for their size while over time μ increases steadily having an increasing influence on the longitudinal handling qualities. The development of the parameter μ is shown in the Figure 3-13.

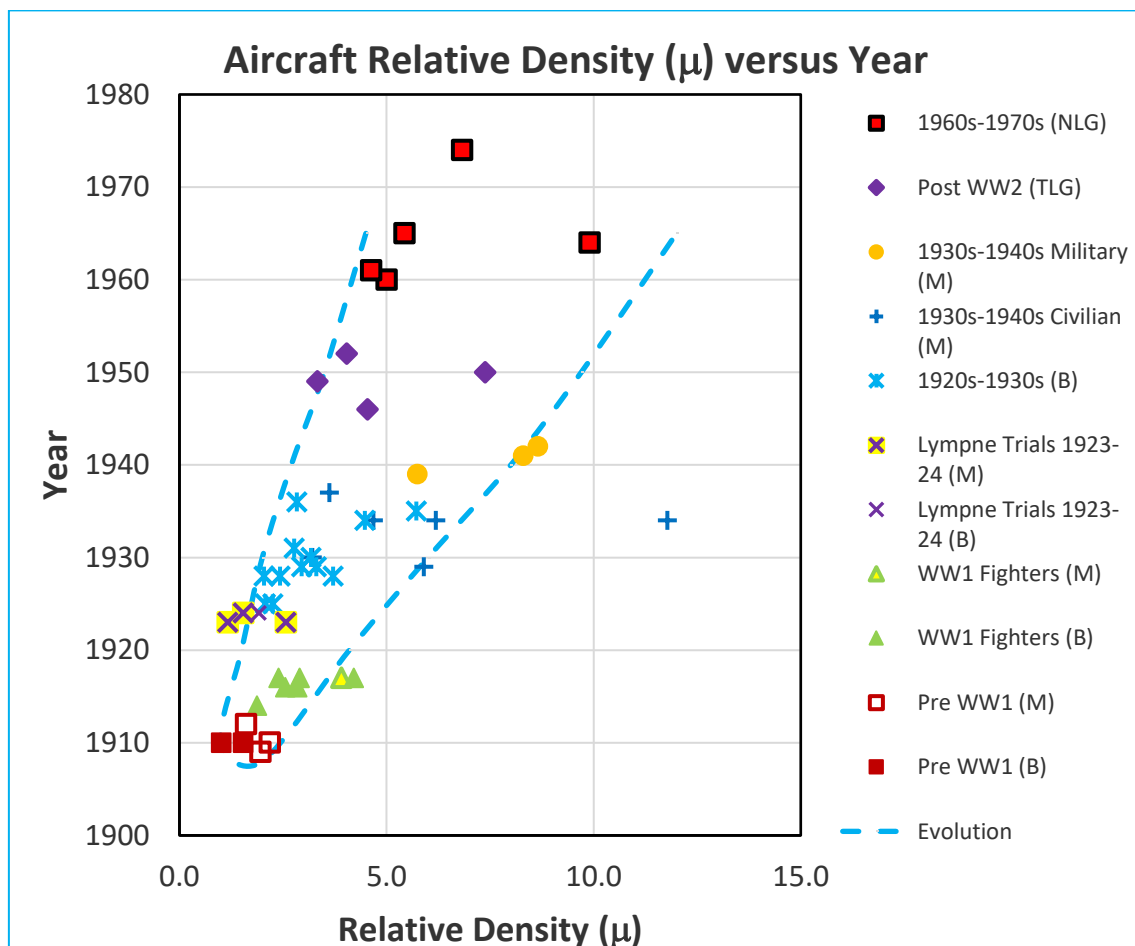


Figure 3-13 - Aircraft Relative Density versus Year

The data in this graph shows a steady increase in μ as aircraft development occurs.

The 1910 Boxtite has the lowest value of relative density ($\mu = 1.0$) due to its large dimensions and lightweight construction. In extreme cases aircraft like this with low mass but very high drag due to the associated wing struts and bracing wires will slow down very rapidly should the engine fail, and its lifting tail will drop in the absence of propeller wash, exacerbating the effect. In this event, given its maximum level speed of 45 mph, it will slow to the stall speed of about 30 mph in just a few seconds if allowed to do so by a non-alert pilot. It will require a very steep nose down attitude to regain and maintain a glide airspeed which is sufficient to permit a flare to a power-off landing, and this may not be achievable from a low height.

At the other end of the scale, with $\mu = 12$ is the 1934 Percival Mew Gull, a racing aircraft designed to enclose the most powerful engine possible and the maximum amount of fuel in the minimum possible volume.

3.2.4 Estimation of pitch damping

Using equation 3-15 the pitch damping derivative C_{Mq} was calculated for all the study aircraft in their respective sub-groups and plotted against year of manufacture in Figure 3-14. A hand drawn line on the figure seeks to trace the way that C_{Mq} changes during the period of study.

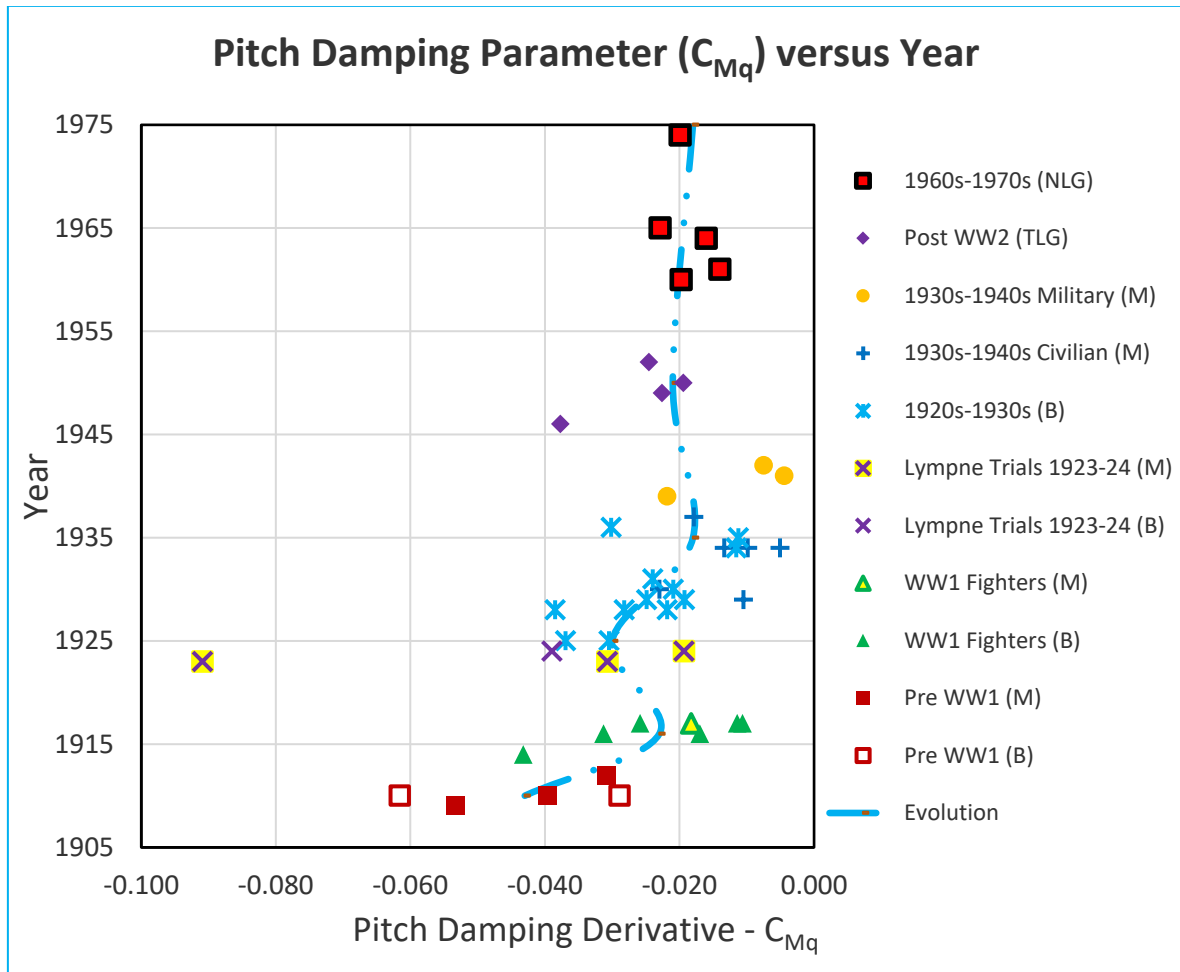


Figure 3-14 - Pitch Damping Derivative (C_{Mq}) versus Year

The pre-WW1 group show the potential for higher levels of pitch damping, but this is due to their low relative density; the ultra-light aircraft in the Lympe Trial group of 1923-24 are similarly affected. For most of the remainder the value stabilises between -0.02 and -0.03 but with some notable outliers. In the WW1 Fighters group the extremes are the 1915 Avro 504K at -0.043 which has a large tail volume and the notoriously twitchy 1917 Sopwith Camel at -0.011 which has a very low tail volume. In the 1923-24 group the wide range exhibited can also be traced to variations in tail volume. Another outlier is the 1934 Percival Mew Gull at -0.005 which has minimal tail volume and is renowned for its pitch sensitivity. Similar pitch sensitivity is reported for the 1940s Hurricane and Spitfire fighters which have comparable values of C_{Mq} .

3.3 Directional parameters

The directional parameters are those that have an effect on the yawing moment coefficient of the complete aircraft and as shown in equation 3.17 below from the United States Air Force Test Pilot School, Flying Qualities Handbook, Volume II (Anon, 1986, p. 7.2)

$$C_{N_{TOTAL}} = C_{N_{\beta}} + C_{N_p} + C_{N_r} + C_{N_{\delta a}} + C_{N_{\delta r}} \quad (3-17)$$

Where $C_{N_{\beta}}$ is due to sideslip angle (β), C_{N_p} is due to roll rate, C_{N_r} is due to yaw rate (yaw damping), $C_{N_{\delta a}}$ is due to aileron deflection (adverse yaw) and $C_{N_{\delta r}}$ is due to rudder deflection (rudder power). The terms C_{N_p} and $C_{N_{\delta a}}$ are cross coupling terms which will be discussed later.

A similar approach to that used in paragraph 3.2 above may be used to examine main directional contributors which affect the coefficient of yawing moment (C_N) of the aircraft due to sideslip angle (β). (Seckel, 1964, p. 243)

$$C_N \beta = C_N \beta_{FUSELAGE} + C_N \beta_{WING} + C_N \beta_{V.TAIL} + C_N \beta_{PROPELLER} \quad (3-18)$$

Where the yawing moment contribution of the vertical tail, $C_N \beta_{V.TAIL}$ can be estimated from:

$$C_N \beta_{V.TAIL} = a_{V.TAIL} \cdot \eta_{V.TAIL} \cdot \bar{V}_{V.TAIL} \quad (3-19)$$

From (Dommasch et al., 1951, p. 474 Eq 15:11)

Where $a_{V.TAIL}$ is the lift curve slope of the vertical tail which can be determined from the effective aspect ratio of the vertical tail ($A_{eV.TAIL}$). The horizontal tail usually acts as an endplate to the vertical tail which has the effect of increasing its effective aspect ratio ($A_{eV.TAIL}$) so equation 3-9 must be modified by a factor of 1.55. (Perkins & Hage, 1949, p. 325 Eq. 8-19)

$$A_{eV.TAIL} = 1.55 \frac{b_{V.TAIL}^2}{S_{V.TAIL}} \quad (3-20)$$

Where $b_{V.TAIL}$ is the height of the vertical tail (usually taken from the tip down to the level of a fuselage mounted horizontal tail), $S_{VT.TAIL}$ is the area of the vertical tail also including the area down to the level of a fuselage mounted horizontal tail.

A relationship between effective aspect ratio and lift curve slope was established in Pass (1940) -Figure 3.

This data has been replotted in Figure 3-15 and the equation of the curve used to estimate $a_{V.TAIL}$ from the calculated value of $A_{eV.TAIL}$. In the group of aircraft being assessed most values of $A_{eV.TAIL}$ are between 2 and 3 and the curve fit in that range is acceptable for the purpose of this study.

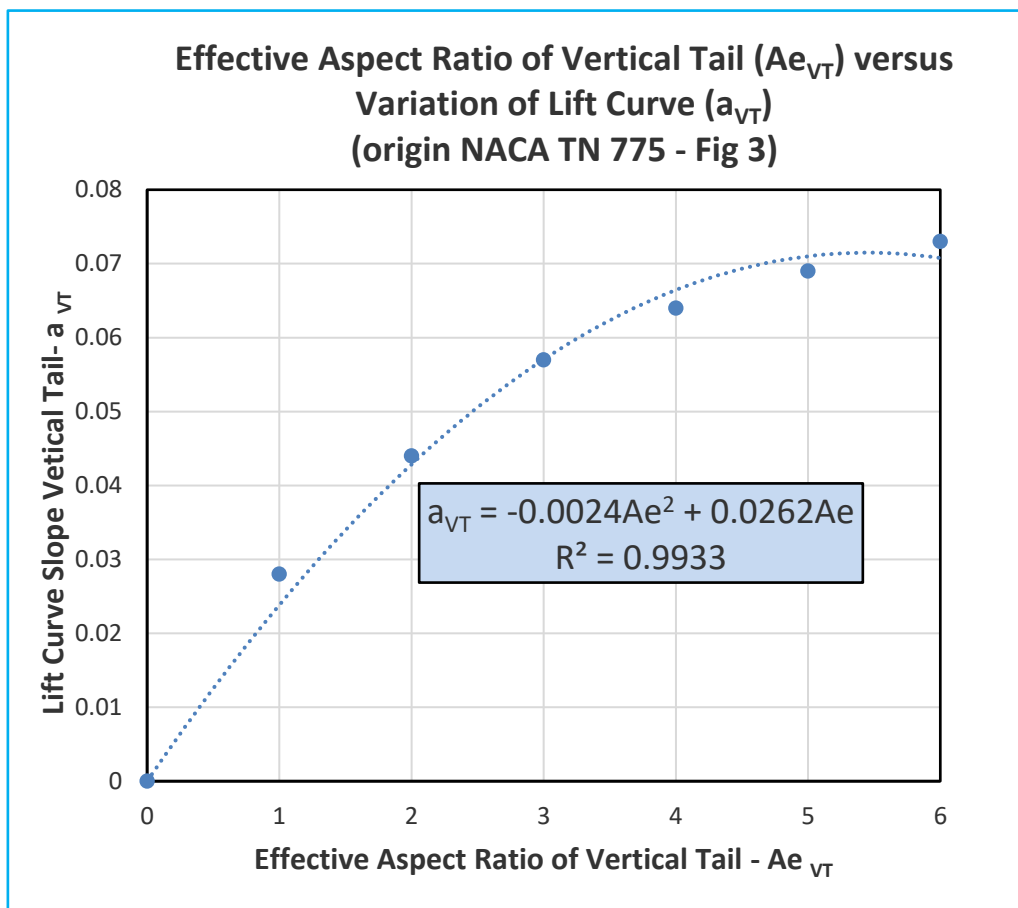


Figure 3-15 - Effective Aspect Ratio of Vertical Tail versus Variation of Lift Curve Slope.

Tail efficiency $\eta_{V.TAIL}$ is as described in para 3.1 above. The third term in equation 3-19 is likely the most significant element of the vertical tail contribution to

directional stability. $\bar{V}_{V.TAIL}$ is the Vertical Tail Volume Coefficient derived from $\bar{V}_{V.TAIL} = (S_{VT}/S_W) (l_{VT}/b_W)$, where S_{VT} is the area of the complete vertical tail, S_W is wing area, l_{VT} the horizontal distance between the ac of the wing and the ac of the vertical tail, and b_W is the wingspan. Thus, the non-dimensional vertical tail volume coefficient and its associated contribution to directional stability can be estimated from components that are easily measured directly from the aircraft or obtained from a scale drawing.

It should be recognised that this derivation of the vertical tail contribution to $dC_N/d\beta$ on its own does not provide everything needed to determine the level of static stability of the aircraft concerned because no evaluation has been made of the other contributors such as wing, fuselage and propeller. However, if the values of $dC_N/d\beta_{Vertical Tail}$ are estimated for a large set of aircraft, useful comparisons may be made.

Using a similar analysis technique, it is possible to estimate other parameters of interest such as Rudder Control Power ($dC_N/d\delta_R$ or $C_N\delta_R$). The power of the rudder to create or oppose yawing moments is a function of the lift curve slope of the vertical tail ($a_{V.TAIL}$), the rudder effectiveness parameter (τ_R), the vertical tail volume coefficient ($\bar{V}_{V.TAIL}$), and the tail efficiency (η_t). (Perkins & Hage, 1949, p. 329 Eq. 8-24)

$$C_N\delta_R = -a_{V.TAIL} \cdot \tau_R \cdot \bar{V}_{V.TAIL} \cdot \eta_{V.TAIL} \quad (3-21)$$

Where the rudder effectiveness parameter (τ_R) is related to the ratio of rudder area (S_R) to the area of the complete vertical tail ($S_{V.TAIL}$).

A relationship between of τ_R to $S_R/S_{V.TAIL}$ was established in (Pass, 1940 Figure 4). This data has been replotted in Figure 3-16 and the equations of the curves used to estimate τ_R from the calculated value of $S_R/S_{V.TAIL}$ and the balance ratio S_B/S_R . The balance ratio is the ratio of the areas of any aerodynamic rudder balance (e.g., horn balance) ahead of the hinge line and the remaining area of the rudder. In the absence of accurate information on rudder balance the curve for $S_B/S_R=0$ has been used in this study. In the group of aircraft being assessed

(ignoring five early fin-less aircraft) most values of $S_R/S_{V.TAIL.}$ are between 0.3 and 0.8 and the curve fit in that range is acceptable for the purpose of this study.

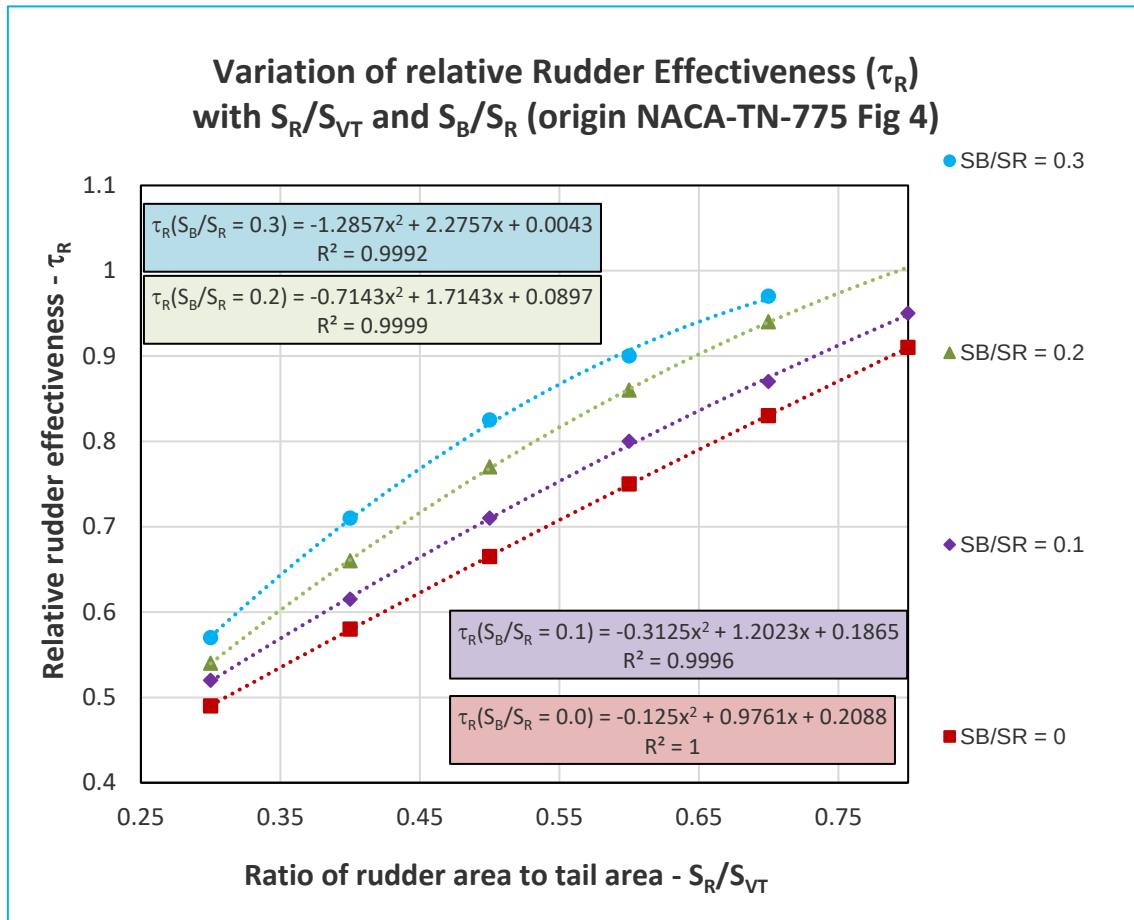


Figure 3-16 – Variation of relative Rudder Effectiveness (τ_R) with Rudder to Vertical Tail Area Ratio (S_R/S_{VT}) and Rudder Balance to Rudder Ratio (S_B/S_R)

The directional stability and control characteristics derived above may be used to examine how design philosophy adapts to external influences such as pilot feedback, war and/or emerging research data.

These derived directional stability and control characteristics have been calculated for 41 aircraft originating from 1909 to 1950. In addition, five typical light aircraft designed in the 1960s and 1970s were also analysed to compare the characteristics of aircraft certificated with the benefit of the extensive stability and control research fallout from the Second World War.

The vertical tail volume, which is the product of tail area and moment arm from the aircraft centre of gravity, is a major factor in both stability and control, being the means by which forces and moments are created from inclinations to the airflow. However, given that such dimensions differ considerably between aircraft it is necessary to convert this into coefficient form, by dividing it by the product of wing area and wingspan ($S_W \cdot b_W$). The values of the resulting vertical tail volume coefficient for different aircraft can then be compared directly.

In Figure 3-17 the vertical tail volume coefficient ($\bar{V}_{VT}$) for each subject aircraft is shown versus its year of manufacture. This shows a significant reduction from the average value of $\bar{V}_{VT}$ in the Pre-WW1 group to the average value of the WW1 Fighters group, the parameter stays low until the mid-1930s before showing a steady increase over the remainder of the period. The upper and lower boundaries are approximate and appear in some textbooks, they appear to be empirical rather than the result of a rigorous analysis.

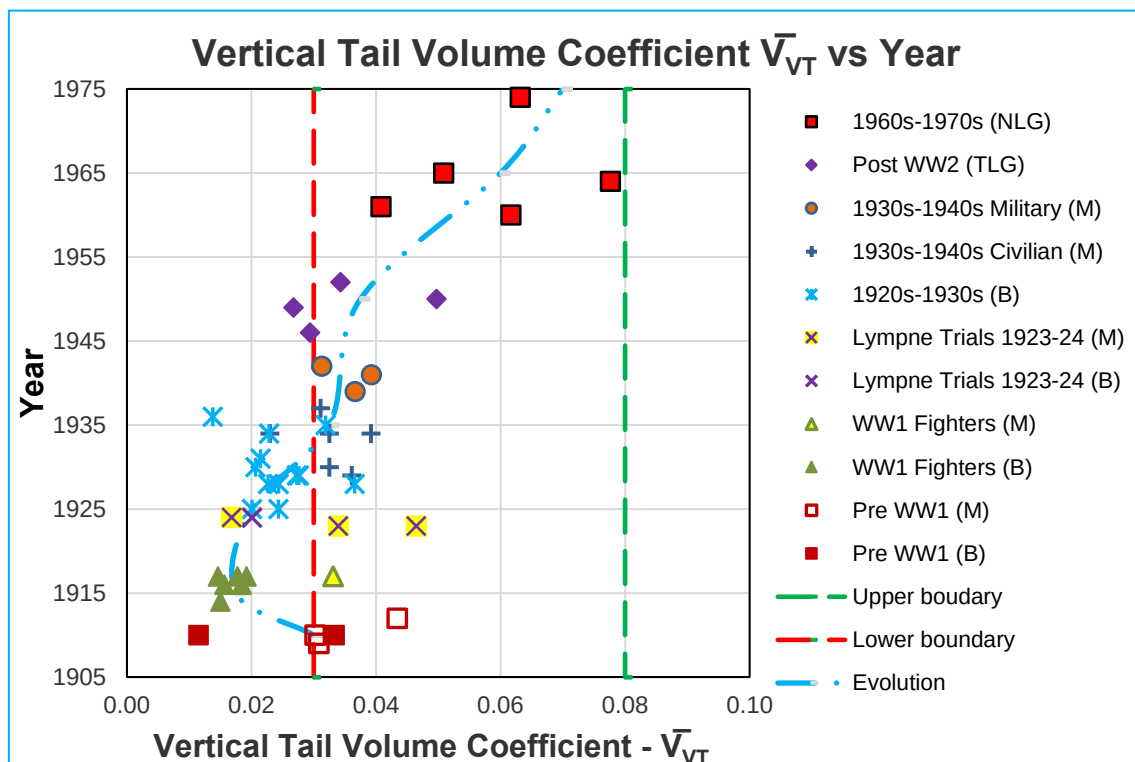


Figure 3-17 - Vertical Tail Volume Coefficient versus Year

This shows that from the Pre WW1 types the $\bar{V}_{VT}$ falls to a low for all the WW1 biplane fighters and, most of the 1920s-1930s biplanes fall below the minimum desired value for this parameter. By the mid-1930's values were just inside the lower boundary. The immediate Post WW2 (TLG) group (fitted with tail wheel landing gear) are marginal whereas the 1960s-1970s (NLG) aircraft (fitted with nose wheel landing gear) enjoy much higher values of $\bar{V}_{VT}$.

Over the period 1905-1955 stalling speeds increased by two to three times and maximum level speeds by an order of magnitude so, as in the longitudinal analysis above, further insight may be gained by examining the product of $\bar{V}_{VT} \cdot \bar{q}_W \cdot \eta_t$ at airspeeds V_S and V_H .

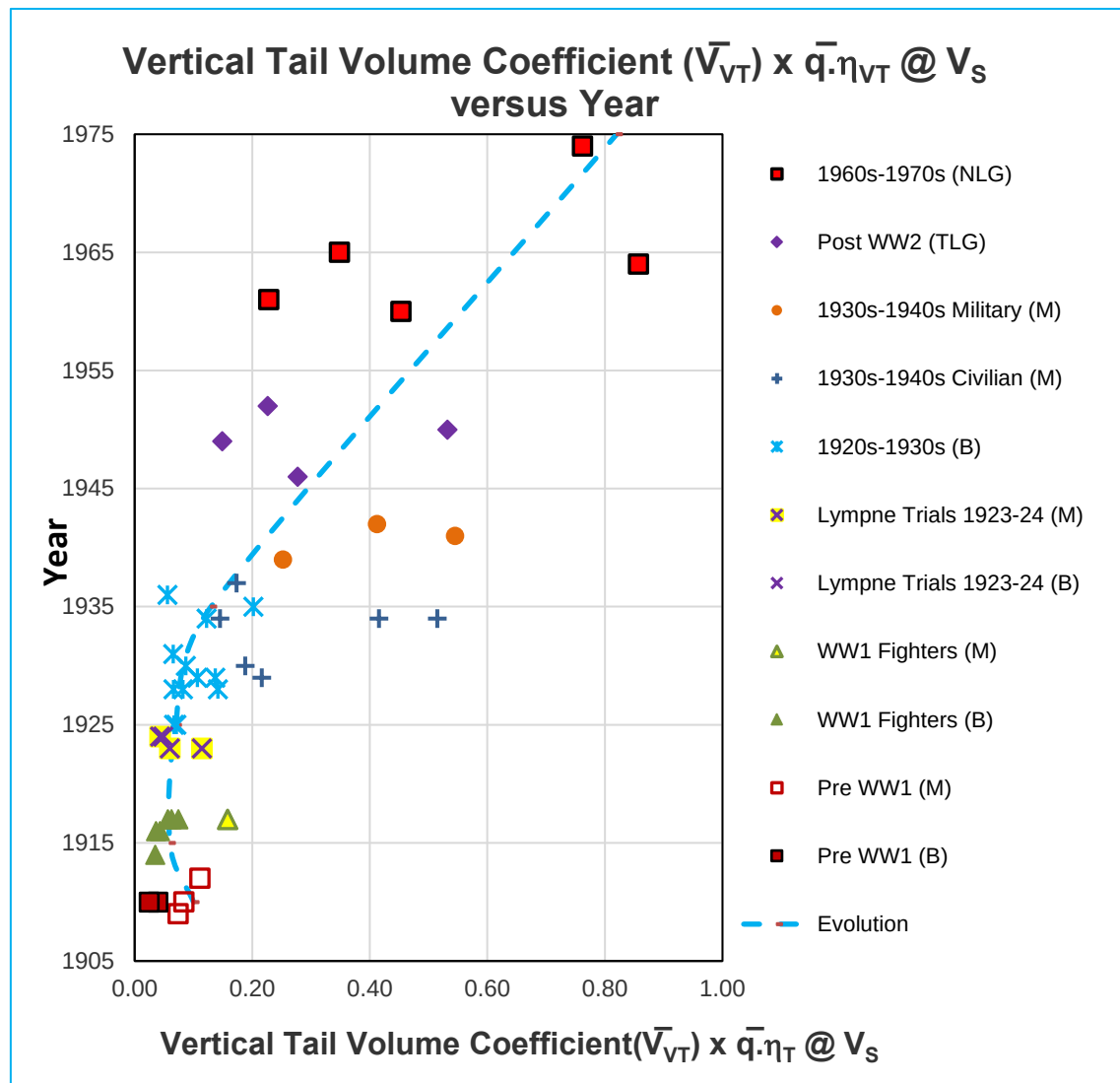


Figure 3-18 - Vertical Tail Volume Coefficient x $\bar{q} \cdot \eta_{VT}$ at V_S versus Year

The evolution of parameter $\bar{V}_{VT} \cdot \bar{q} \cdot \eta_{VT}$ (where the q used is that at the stalling speed V_S) can be seen to reduce somewhat from the Pre-WW1 era to WW1 then increase very slightly until the mid-1930s – thereafter the parameter shows a steady increase as vertical tail volumes and stalling speeds increase over time.

As shown in Figure 3-19, when the q used is that for the aircrafts' maximum level flight speed V_H , the evolution is different in that it is lowest for the Pre WW1 types because of their very restricted speed ranges. It increases into the WW1 era, falls back for the ultra-low powered Lypne Trials aircraft (low values of V_H). The 1920s-1930s biplanes have the same value as the WW1 aircraft but thereafter the parameter shows a marked increase as both V_H and $\bar{V}_{VT}$ increase over time.

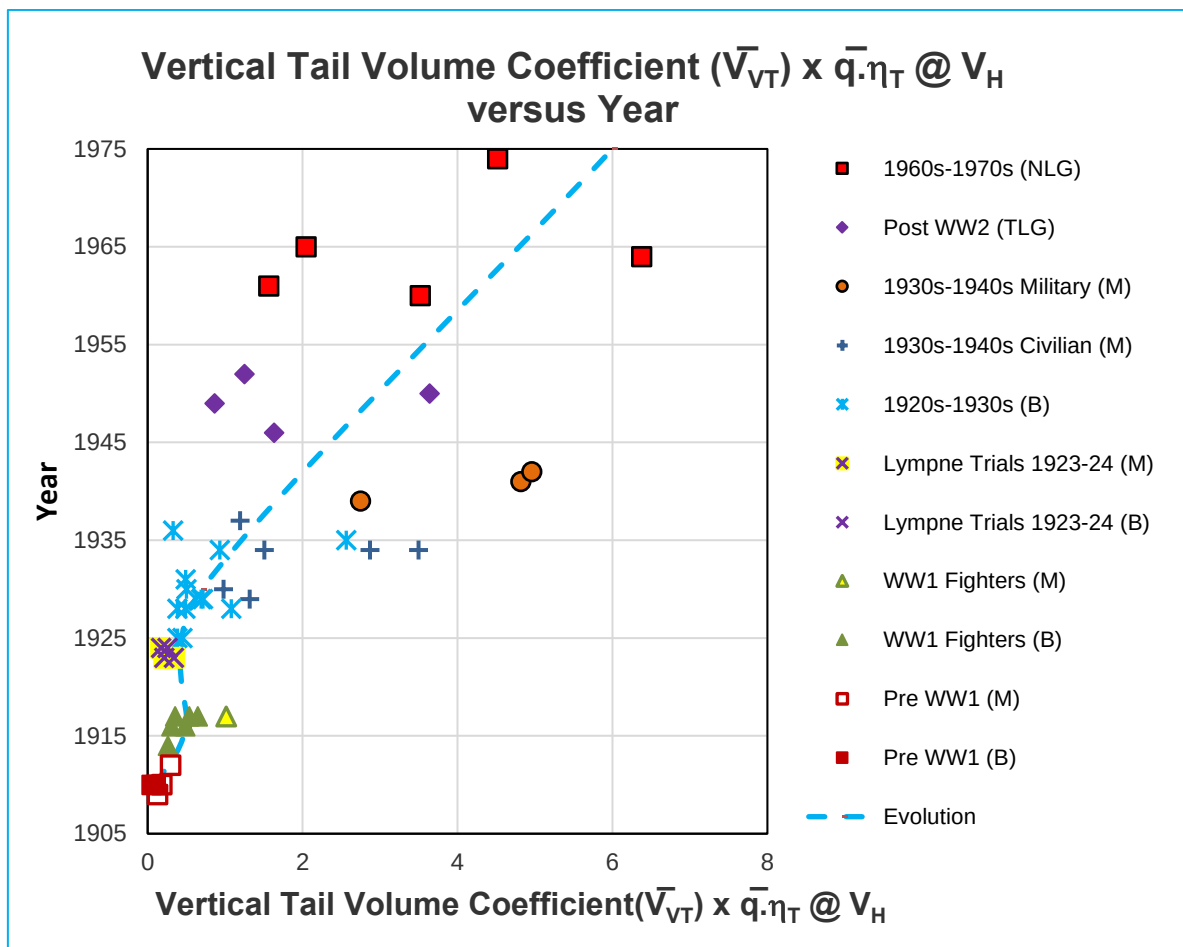


Figure 3-19 - Vertical Tail Volume Coefficient x $\bar{q} \cdot \eta_{VT}$ at V_H versus Year

Here the WW1 monoplane fighter (Bristol M1c 1917) appears as an outlier at just over 1 unit, and this is in part due to having a value of $\bar{V}_{VT}$ double the average of the other WW1 types analysed. The Bristol M1c is known to exhibit moderate directional static stability whereas the stability of the remaining WW1 types is known to be very much lower. Another outlier can be seen in 1934, at just over 3.5 units this is the DH-88 Comet Racer which enjoyed one of the highest maximum level flight speeds at that time of 220 MPH. The two points around 1940 are the Hawker Hurricane (Fighter) and the Vickers Supermarine Spitfire (Fighter) which, as interceptors, have high values of V_H hence the high scores. The 1964 Sia Marchetti 260 scores approximately 6.5 which is in part due to high V_H but also because it has the highest value of $\bar{V}_{VT}$ due to a substantial dorsal fin..

3.3.1 Estimation of the contribution to directional static stability of the complete vertical tail

The contribution of the complete vertical tail to directional static stability $dC_N/d\beta$ (*V. TAIL*) (equation 3-19) was evaluated for each subject aircraft and, assuming that all the other contributions to directional static stability for these subject aircraft are similar, this parameter is indicative of the relative level of controls-fixed directional stability.

In Figure 3-20, the parameter $dC_N/d\beta$ (*V. TAIL*) is plotted against year of manufacture.

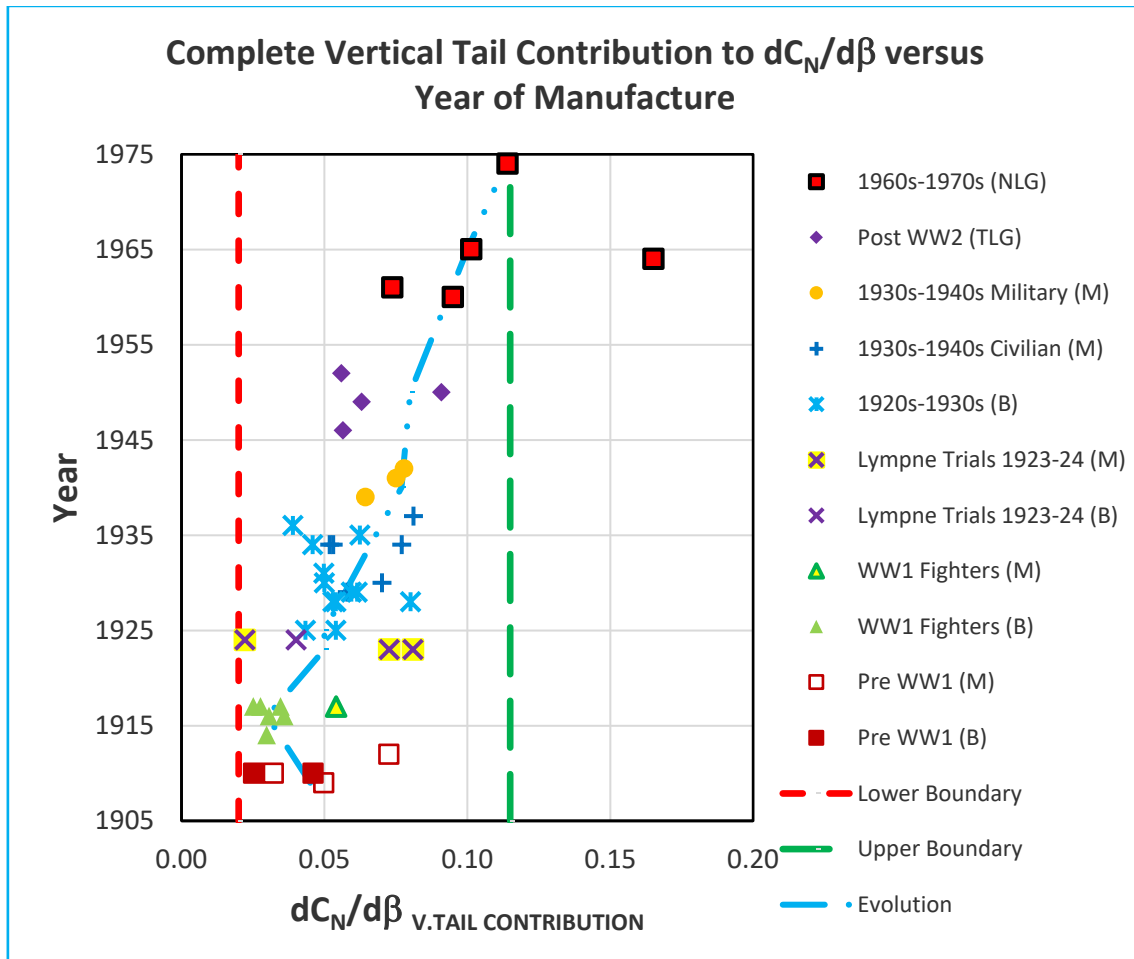


Figure 3-20 - Complete Vertical Tail Contribution to Directional Static Stability vs Year

This shows a minimum in the WW1 period remaining low into the 1930s followed thereafter by steady increase over time. This parameter is indicative of the potential for rudder-fixed directional static stability, but this does not paint the complete picture as it assumes that the entire rudder area is fixed in a neutral position and therefore is acting as a vertical stabiliser, assisting the fixed fin (if any). However, examining the fin and rudder separately shows how the ratio of these surfaces has changed over the period.

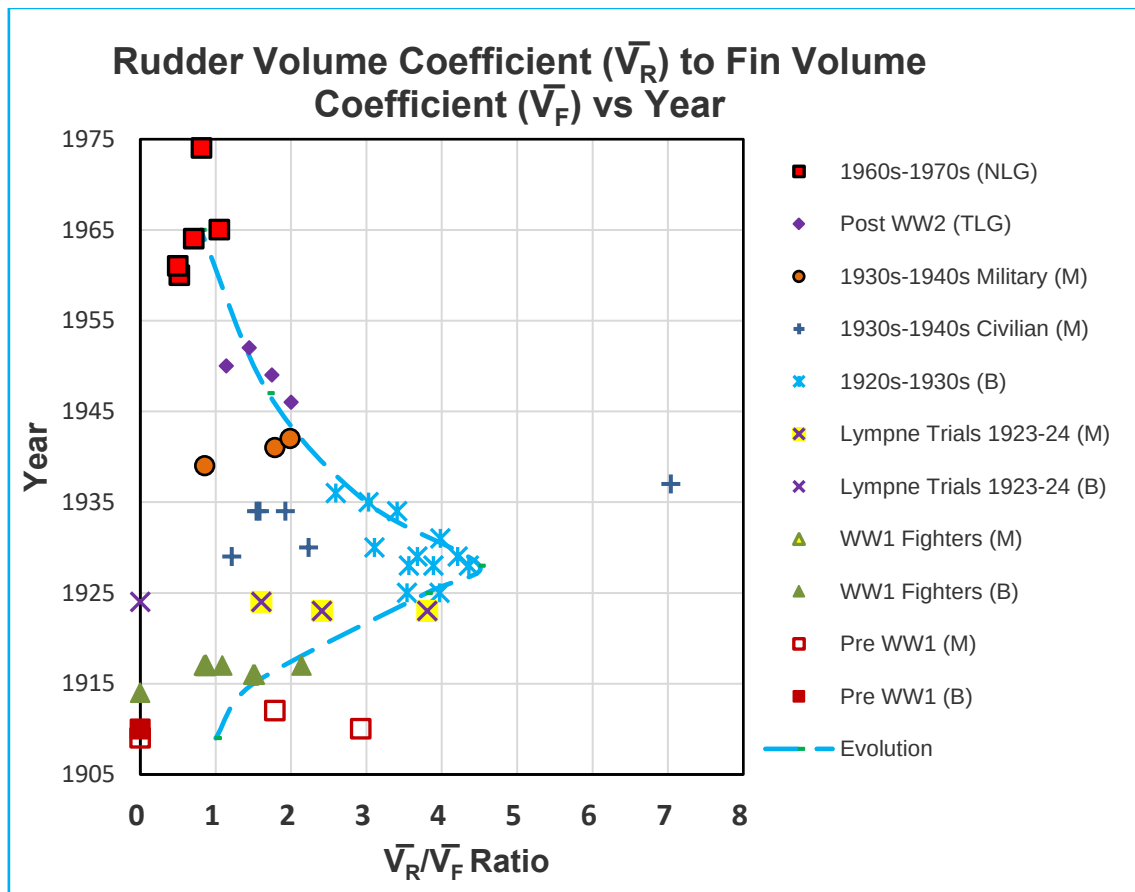


Figure 3-21 - Rudder to Fin Volume Ratio versus Year

Figure 3-21 shows clearly how this parameter peaks in 1920-1930s biplanes but with one significant outlier the monoplane Miles Magister with a ratio of 7.

To achieve the level of directional stability contribution suggested by Figure 3-20 the pilot will need to restrain the rudder in or near the neutral position and the effort required to do that depends on any aerodynamic balance devices fitted. To assess how this parameter might change with the rudder released (and free to trail, thereby making no contribution to stability) the plot can be remade using the fixed fin volume coefficient only.

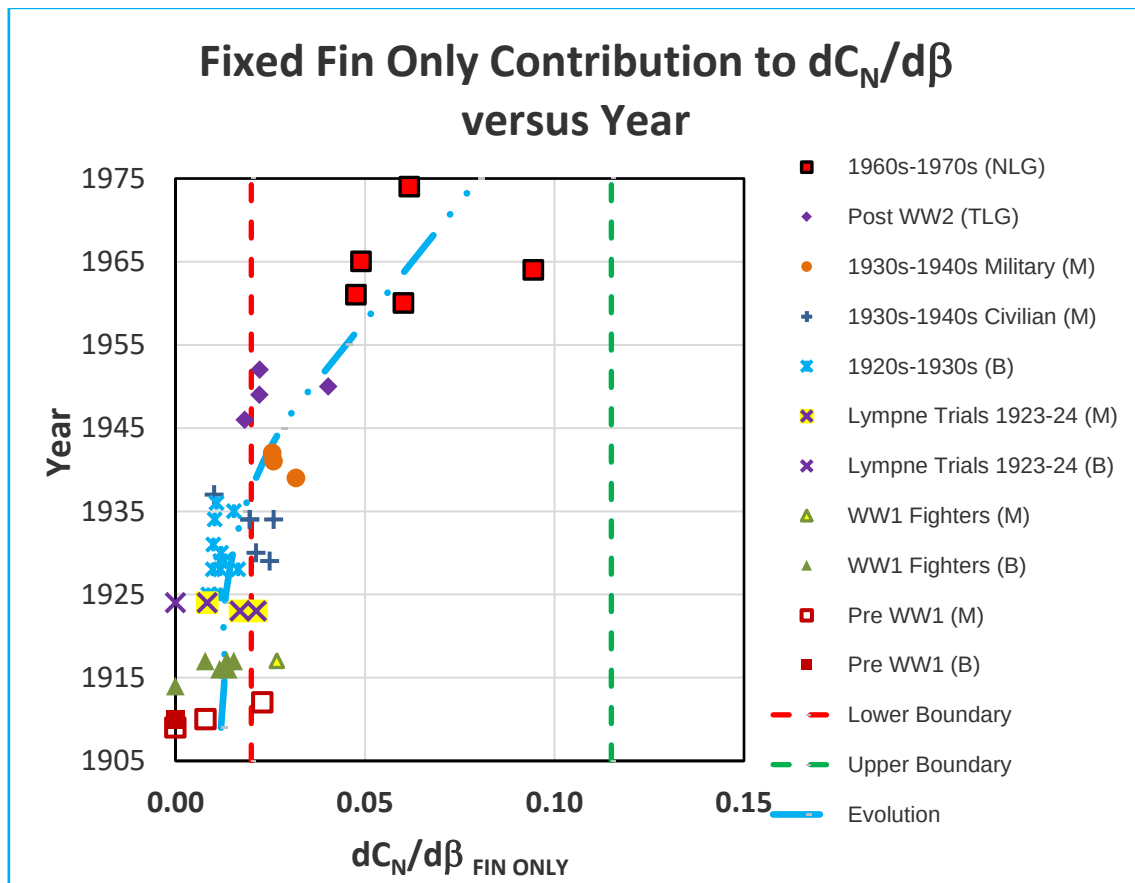


Figure 3-22 - Fixed Fin Contribution to Directional Static Stability vs Year

The upper and lower boundaries shown in Figures 3-20 and 3-22 are taken from (Perkins & Hage, 1949, p. 326)

Figure 3-22 shows that until around 1935 few aircraft were likely to have acceptable directional static stability from the fixed fin meaning that the pilot had to compensate by acting in a directional stability augmentation role. In the Pre WW1 group, only the Blackburn of 1912 shows an acceptable level of fixed fin contribution to directional stability. Similarly, in the WW1 Fighters group only the 1917 Bristol M1c monoplane is above the recommended minima. Between 1925 and 1935 none of the biplanes exceed the minimum requirement and, of the civilian monoplanes in the 1930-1940 era, only the Comper Swift, Desoutter Mk 1 and Percival Mew Gull are above the 0.02 level, although the DH-88 Comet is only just below at 0.0196. Thereafter, all aircraft are above the minimum requirement and the level of the fixed fin contribution to directional static stability increases. The large step between the Post WW2 group and the 'control' group

of the 1960-1970s is that the former have tailwheel landing gear i.e. tail wheels, while the latter have 'tricycle' landing gear i.e., nose wheels. Because the tricycle layout usually provides direct steering through the nosewheel when on the ground the rudder size can be reduced, and the fin size becomes relatively larger. If a comparison is made between Figure 3-20 and 3-22 it is evident that the 1960s-1970s aircraft, with an average level of $dC_N/d\beta$ (*FIXED FIN ONLY*) of around 0.06, are better in this regard than most of the earlier aircraft when their rudders are included as part of the vertical stabiliser. This represents a very large difference to the pilot in terms of the compensation required for any given lateral flight task and makes the later aircraft easier to fly and less prone to mishandling.

3.3.2 Estimation of rudder control power

As shown in equation 3-21 above it is also possible to estimate rudder control power ($dC_N/d\delta_R$) using parameters derived by the analysis. Both $dC_N/d\beta$ (*V. TAIL*) (equation 3-19) and $dC_N/d\delta_R$ rely on the product of the vertical tail volume coefficient $\bar{V}_{VT}$ and the tail efficiency factor η_T , while equation 3-19 contains the lift curve slope of the vertical tail (a_{VT}) (from Figure 3-15) and the rudder effectiveness parameter (τ_R) (from Figure 3.16). Therefore, the two parameters, $dC_N/d\beta$ (*V. TAIL*) and $dC_N/d\delta_R$ will have similar characteristics and will follow trends in $\bar{V}_{VT}$ shown in Figure 3-17.

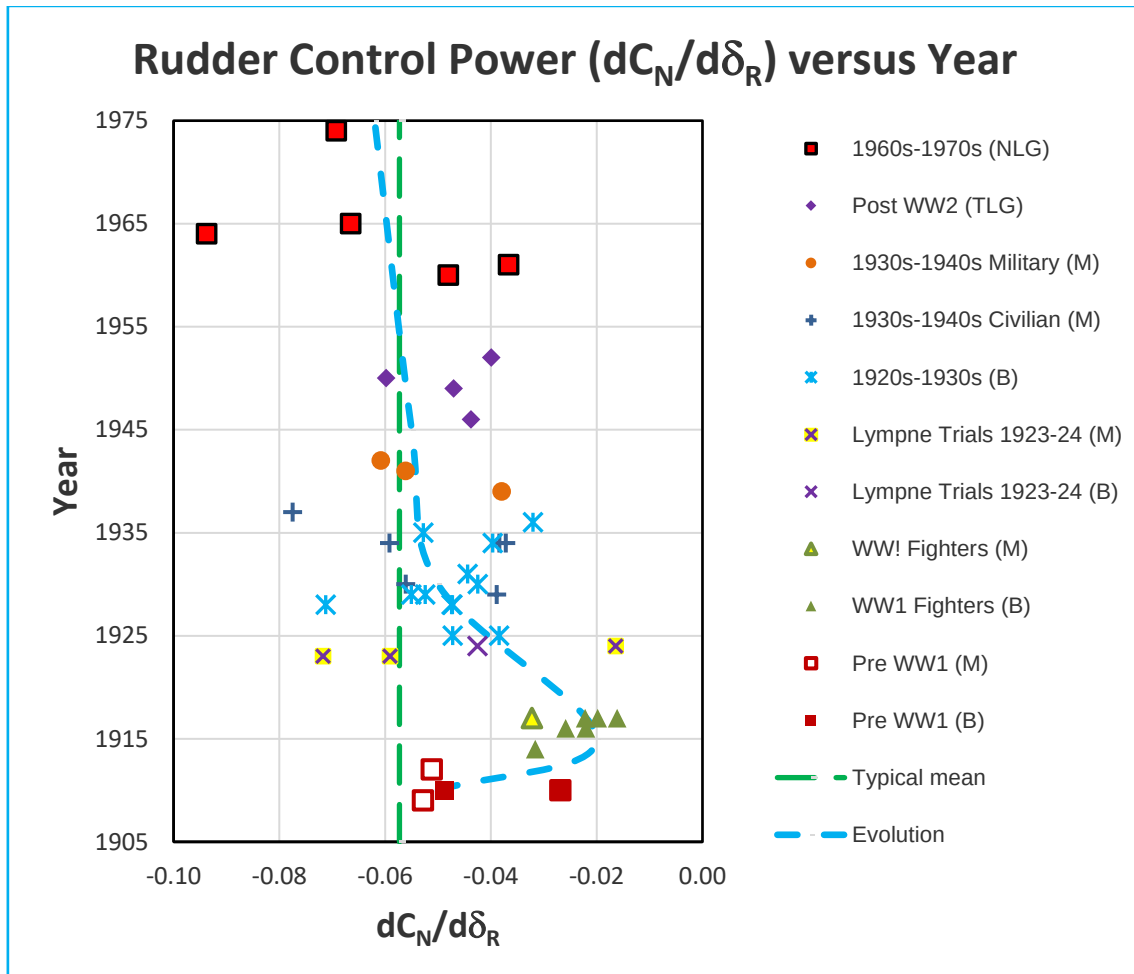


Figure 3-23 - Rudder Control Power versus Year of Manufacture

Figure 3-23 shows how the rudder control power (as derived from equation 3-21) has changed over the period. The typical mean value at $-0.0573/\text{radian}$ originates from (Perkins & Hage, 1949, p. 329) which states ‘On normal airplane configurations, the rudder power varies considerably between airplanes, but a good mean value can be taken as $C_{N\delta_R} = -0.001$ [per degree].’

Given this reference was published in 1949, and probably based on WW2 aircraft, their suggested mean value correlates with the estimated ‘Evolution’ line after 1940.

However, any pilot who has flown WW1 fighters will testify that they do not seem to be as deficient in rudder power as this graph implies. One way of assessing rudder sensitivity (sensitivity is chosen to avoid confusion with rudder

control power ($dC_N/d\delta_R$) and rudder effectiveness parameter (τ_R), is to estimate the sideslip angle that results per degree of rudder deflection ($d\delta_R/d\beta$).

$$\frac{dC_N}{d\beta} \cdot \frac{d\delta_R}{dC_N} = \frac{d\delta_R}{d\beta} \quad (3-22)$$

This is the slope of the line of a plot of sideslip angle versus rudder deflection. In the absence of flight test or wind tunnel data an equivalent may be derived from estimates of $dC_N/d\beta$ and $dC_N/d\delta_R$.

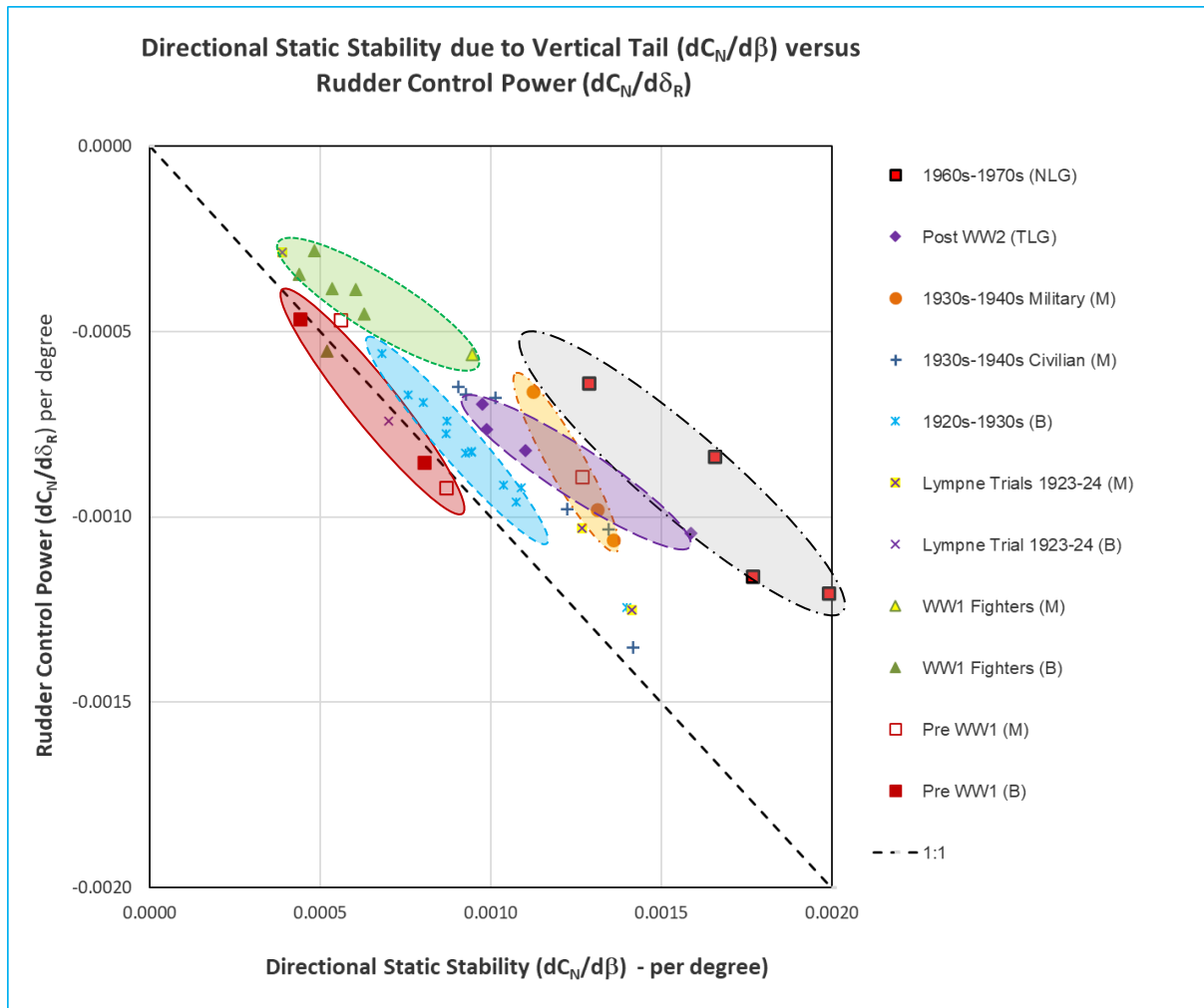


Figure 3-24 - Directional Static Stability versus Rudder Control Power

In Figure 3-24 these parameters are plotted for the aircraft in the study. The dashed line represents the condition where one degree of rudder produces one

degree of sideslip. Main groupings by era are shown in the coloured shapes. The red area shows aircraft which have no fixed vertical stabiliser but have an all-moving rudder – these include Pre WW1 types, the early WW1 Avro 504K and the 1924 ultralight Cygnet. The green area represents the remainder of the WW1 fighters. The blue area contains the 1920s-1930s biplanes. The purple area and the orange area represent WW2 and immediate Post WW2 types. The grey area the 1960-1970s types. The trend is that the contribution to directional static stability increases with time and as that progresses the amount of sideslip that can be produced for a given rudder deflection reduces.

There are many surviving aircraft from the 1920s-1930s biplane era but now flown by pilots who will have trained on aircraft from the 1960s-1970s area. Such pilots will not expect the rudder control to be capable of producing such large sideslip angles or the implications on handling qualities; particularly at low airspeed when these aircraft have poor roll power.

The aircraft in the blue area are all biplanes which are not equipped with landing flaps. In such aircraft, to adjust his glide slope angle the pilot performs a deliberate sideslip to increase drag and thereby steepen the approach path as required. Therefore, it is important that the rudder can produce sufficient sideslip to create a meaningful increase in drag – the higher the rudder control power and the lower the directional static stability the greater the sideslip angle the rudder can generate and the greater the drag control available. However, when in normal symmetric flight these characteristics leave the aircraft with either, deficient controls free directional static stability or, an overly powerful rudder (or both) which may require considerable pilot compensation. Only a small proportion of biplanes were equipped with differential wheel brakes, which assist directional control when on the ground, so the combination of low directional static stability and high rudder power also allows them to be taxied in out-of-wind directions before and after flight. Most monoplanes (purple and orange areas) are equipped with differential wheel brakes and landing flaps which steepen the landing approach glide so the requirement to generate high angles of sideslip is lessened but a powerful rudder is still required to maintain

control in cross wind operations particularly for aircraft with tailwheel landing gear. In Figure 3-24 there is an interesting outlier at 0.0014/-0.0014 which is the Miles Magister, also shown in Figure 3-21. This is a monoplane equipped with flaps and differential wheel brakes so one would expect it to be close to the other monoplanes in its group, but for reasons now uncertain the proportions of its vertical surfaces reflect earlier 'flapless biplane' thinking. Whereas the other aircraft in its group have rudder to fin ratios between 1 and 2; for the Magister it is 7. Such an apparently inappropriate design feature may arise if the original prototype had neither flaps nor brakes and the vertical tail was not then redesigned when such enhancements were added. Whatever the reason it creates a trap for the unwary as it allows excessive sideslip to occur. Sideslipping in this aircraft produces a marked nose down pitching moment, particularly so at high airspeed, and this resulted in several accidents prompting an investigation by the Royal Aircraft Establishment. (Lyons, 1939)

This requirement for sideslip capability is further reduced if the aircraft is also equipped with nose landing gear because, unlike tail gear aircraft, this layout is directionally stable when rolling on their wheels. Therefore, these aircraft can have higher levels of directional static stability and relatively lower rudder control power, and this is illustrated in Figure 3-23 for the 1960s-1970s (NLG) group. Their inflight directional handling qualities are vastly superior and will maintain balanced flight with minimal pilot compensation.

The post WW2 ideal for rudder control characteristics is illustrated by the following extract from a RAE report on handling criteria. (O'Hara, 1966)

'The rudder has received little attention in recent handling research, probably for the simple reason that it is not regarded as a primary means of control except in special circumstances such as engine failure, cross wind landing, or spin recovery; in normal flight conditions, the rudder is used to maintain zero sideslip, to counteract directional trim change with speed or power, or for coordination in a turn. Pilots object to the need for excessive rudder coordination and indeed the ideal seems to be virtually no rudder

coordination. The only other requirements in relation to the rudder control appear to be of the following general kind:

- (a) Rudder angle and pedal force should vary linearly with sideslip over a reasonable range*
- (b) The rudder should self-centre, but the breakout force should not be excessive.'*

The directional characteristics of many vintage aircraft as discussed in the preceding analysis are very different from this post-WW2 ideal.

Directional handling qualities are also affected by the moment of inertia about the normal axis (I_{zz}). As described in the treatment of Longitudinal parameters above, values of I_{zz} were derived from the I_{zz} curve fit in Figure 3-12.

3.3.3 Estimation of yaw damping

Another directional parameter of interest is yaw damping i.e. yawing moment due to yaw rate N_r or non-dimensional C_{N_r} . This parameter is a factor in the Dutch roll and spiral modes which are discussed later. The vertical tail contribution of this parameter is most dominant and can be estimated using an equation found in (Dommasch et al., 1951, p. 480 Eq. 15.21B)

$$C_{N_r} = -57.3 \frac{dC_{LT}}{d\alpha_T} \cdot \frac{2l^2}{b^2} \cdot \frac{q_T}{q} \cdot \frac{S_T}{S_W} \quad (3-23)$$

Where, $dC_{LT}/d\alpha_T$ is the lift curve slope of the vertical tail (derived from Figure 3-15), ' l ' is the distance from the centre of gravity to the vertical tail and ' b ' is the wingspan, q_T/q is the tail efficiency factor η_T , and S_T and S_W the areas of the vertical tail and wing respectively.

It is of interest to examine how the magnitude of yaw damping changed over time as shown in the Figure 3-25. It should be noted that the WW1 Fighters typically have very low yaw damping which means that, particularly for those aircraft in that group fitted with rotary engines, considerable or extensive pilot compensation is necessary to maintain accurate directional control.

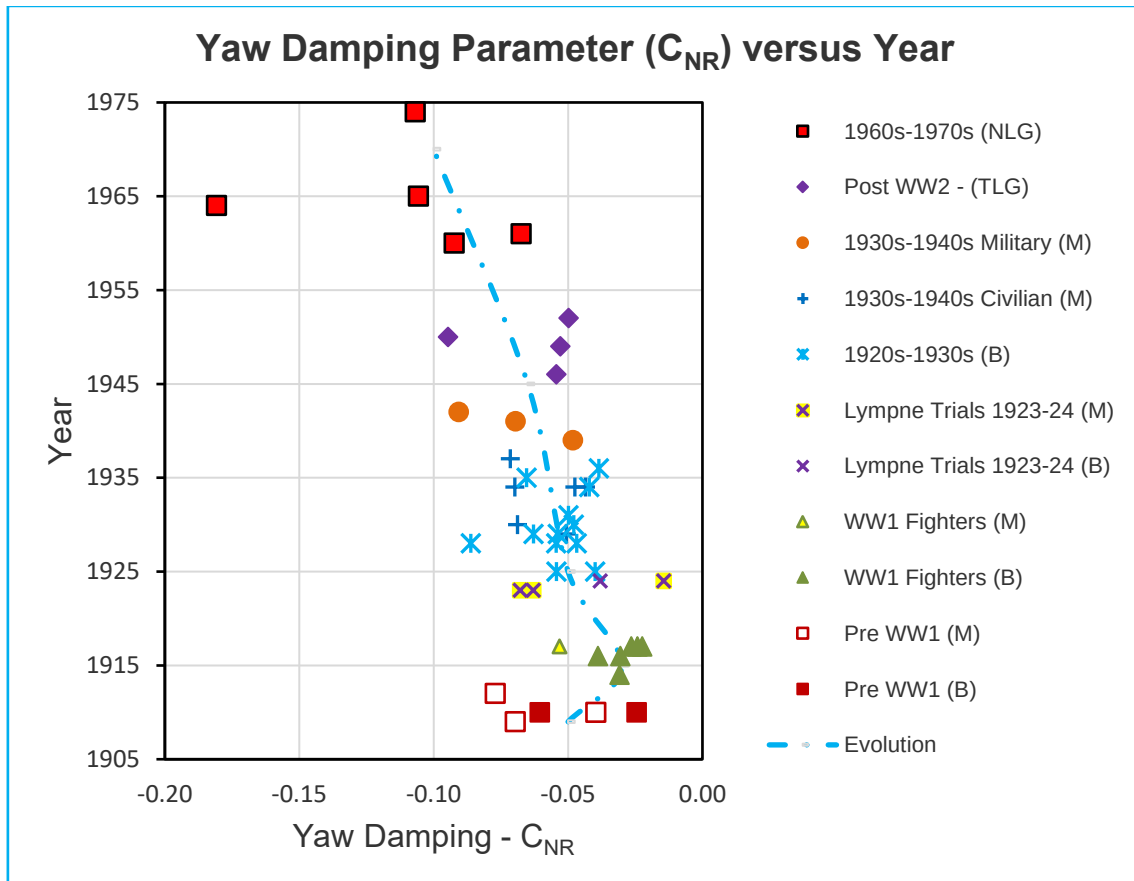


Figure 3-25 - Yaw Damping (C_{Nr}) versus Year

This shows how yaw damping was generally low in the first three decades but thereafter increases to twice the early value by the 1940s and further still for the later aircraft. Since many of the elements in equation 3-23 are contributors in directional static stability it is likely that the improvement in yaw damping is following a similar trend to that seen in Figure 3-20. As the transition from flapless, brakeless biplanes into monoplanes with flaps, differential wheel brakes and much higher top speeds took place, the need for sideslipped approaches diminished while the requirement to avoid inadvertent sideslipping at the higher speeds became essential. This led to larger, more effective vertical stabilisers which can provide enhanced yaw damping.

3.4 Lateral parameters

A similar approach to that used in paragraph 3.2 above may be used to examine characteristics which have a bearing on the lateral stability* and control characteristics.

This section concerns parameters affecting the rolling moment of the aircraft ($\mathcal{L}$) the main contributors are shown in equation 3-24:

$$\mathcal{L}_{\text{AIRCRAFT}} = \mathcal{L}_{\text{SIDESLIP}} + \mathcal{L}_{\text{AILERON}} + \mathcal{L}_{\text{YAW RATE}} + \mathcal{L}_{\text{ROLL RATE}} \quad (3-24)$$

Where $\mathcal{L}_{\text{SIDESLIP}}$ is the rolling moment due to sideslip also known as ‘dihedral effect’, and $\mathcal{L}_{\text{AILERON}}$ is the rolling moment due to aileron deflection or ‘roll power’. For completeness $\mathcal{L}_{\text{YAW RATE}}$ is the rolling moment due to the differential airspeed over left and right wings when yawing and $\mathcal{L}_{\text{ROLL RATE}}$ is roll damping which rapidly damps a roll acceleration to a steady roll velocity.

[*The term ‘lateral stability’ is often used in this area, but this can be misleading as there is no rolling moment due to roll angle. The use of the term lateral stability probably originates in the earliest days of flight when many protagonists adopted terms from naval architecture such as pitch, roll and yaw and furthermore assumed that the physical principles of boats also applied to heavier than air flying machines. In ship design an essential for safety is ‘self-righting’ in roll although if the design limit is exceeded the vessel will capsize. But this self-righting capability arises from the relationship between the vessel’s centre of gravity and its centre of buoyancy such that as it rolls the centre of buoyancy is displaced laterally creating a moment about the centre of gravity to provide a stabilizing effect. This effect is present whether the vessel is floating stationary or travelling through the water. There is no direct equivalent in aircraft, but nevertheless flight pioneers felt that aircraft would ‘capsize’ if banked ‘too much’. This misunderstanding had many unintended consequences on the design and characteristics of some pre-WW1 aircraft. There were accidents through uncontrollable rolling until impact which were often wrongly diagnosed as ‘capsizes’. More likely they were stall-spin departures (in an era when little was known about either) or alternatively a spiral divergence coupled with inadequate roll control power. Furthermore, certain combinations of lateral and directional characteristics, such as strong dihedral effect coupled with significant adverse yaw, can render the lateral control system incapable of stopping a roll divergence and may even exacerbate it.]

3.4.1 Estimation of dihedral effect (rolling moment due to sideslip)

The characteristic most resembling a 'lateral stability' is the first term in equation 3-24 which is 'rolling moment due to sideslip angle' ($C_L\beta$).

$$C_{L\beta} = C_L\beta_{DIHEDRAL} + C_L\beta_{WING\ SWEEP} + C_L\beta_{VERTICAL\ TAIL} + C_L\beta_{WING/FUSELAGE} \quad (3-25)$$

This is usually referred to as 'dihedral effect' because the biggest contributor to this is usually the effective dihedral, but other contributions include swept back wings, a tall or high aspect ratio vertical stabiliser and the vertical location of the wing on the fuselage.

Of these four elements it is the dihedral which has the greatest effect for straight wing ($\Delta=0$) aircraft so that will be examined first. This is a function of the effective dihedral angle (Γ_{eff}), the lift curve slope of the wing (a_w), the ratio of the distance ($\bar{y}$) from the plane of symmetry to centre of lift of the wing panel having dihedral to the wingspan (b_w) thus $\bar{y}/b_w$, and the ratio of the wing area having dihedral to the total wing area (S_Γ/S_w).

$$\frac{dC_L}{d\beta} = -\frac{2\Gamma_{eff}}{57.3} a_w \frac{\bar{y}}{b_w} \frac{S_\Gamma}{S_w} \quad (3-26)$$

(Dommasch et al., 1951, p. 486 Eq. 15:30)

Given the types of historical aircraft in this study wing sweep is not a significant factor so will not be analysed further. Similarly, most of the vertical tails of the historic aircraft in this study are of low aspect ratio (varying between 1 and 4) so they are unlikely to make a significant contribution.

The effect of the wing to fuselage relationship can have a marked effect on dihedral effect. Many of the aircraft in this study are biplanes where the effect of the upper and lower wings cancels out but, of the monoplanes in the study, there are high, low, mid and shoulder wing layouts.

'There is no analytical method of accurately estimating this effect however it has been demonstrated by tests that a straight wing with no geometric dihedral or

sweep will give the equivalent of from 1° to 3° of positive effect dihedral when installed as a high wing. The same wing will give the equivalent of 1° to 3° negative effective dihedral when installed as a low wing. The mid wing location gives approximately zero dihedral effect.' (Dommasch et al., 1951, p. 490)

In this study, the effect of wing/fuselage position on the dihedral angle is taken as follows: high wing = +2°, shoulder wing = +1°, biplane and mid-wing = 0, low wing = - 2°.

The effective dihedral angle (Γ_{eff}) is the algebraic sum of the geometric dihedral (Γ) and the correction for wing/fuselage position assumed above. It is the value of Γ_{eff} that is used in equation 3-26.

It should be recognised that this derivation of dihedral effect contribution to lateral static stability ($dC_L/d\beta$) on its own does not provide everything needed to determine the level of lateral stability of the aircraft concerned because no evaluation has been made of the other contributors such as the fin contribution or yaw and roll rates. However, if the values of $dC_L/d\beta_{DIHEDRAL EFFECT}$ are estimated for a large set of aircraft useful comparisons may be made.

In the longitudinal and directional cases pitching and yawing moments result when the aircraft reacts to the angle of attack (α) and angle of sideslip (β) respectively. As discussed above there is no direct equivalent in the lateral case since roll angle (ϕ), taken in isolation, cannot generate a rolling moment. However, rolling moments may be created if the aircraft develops a sideslip angle.

The aircraft may develop a sideslip angle for many reasons including:

- a side force for example from the lateral component of lift when the aircraft is at a non-zero roll angle but not in a co-ordinated turn.

- or the rudder is deflected from its 'trim' position,

- or yaw results from deflections of the roll control system and the resulting roll rate,

- or propeller induced yaw.

Sideslip angles thus created will result in a rolling moment for all non-zero values of $dC_L/d\beta$, or $C_L\beta$.

Figure 3-26 shows the estimated rolling moment due to sideslip ($C_L\beta$) resulting from the effective dihedral angle (Γ_{Eff}) of the aircraft in the study.

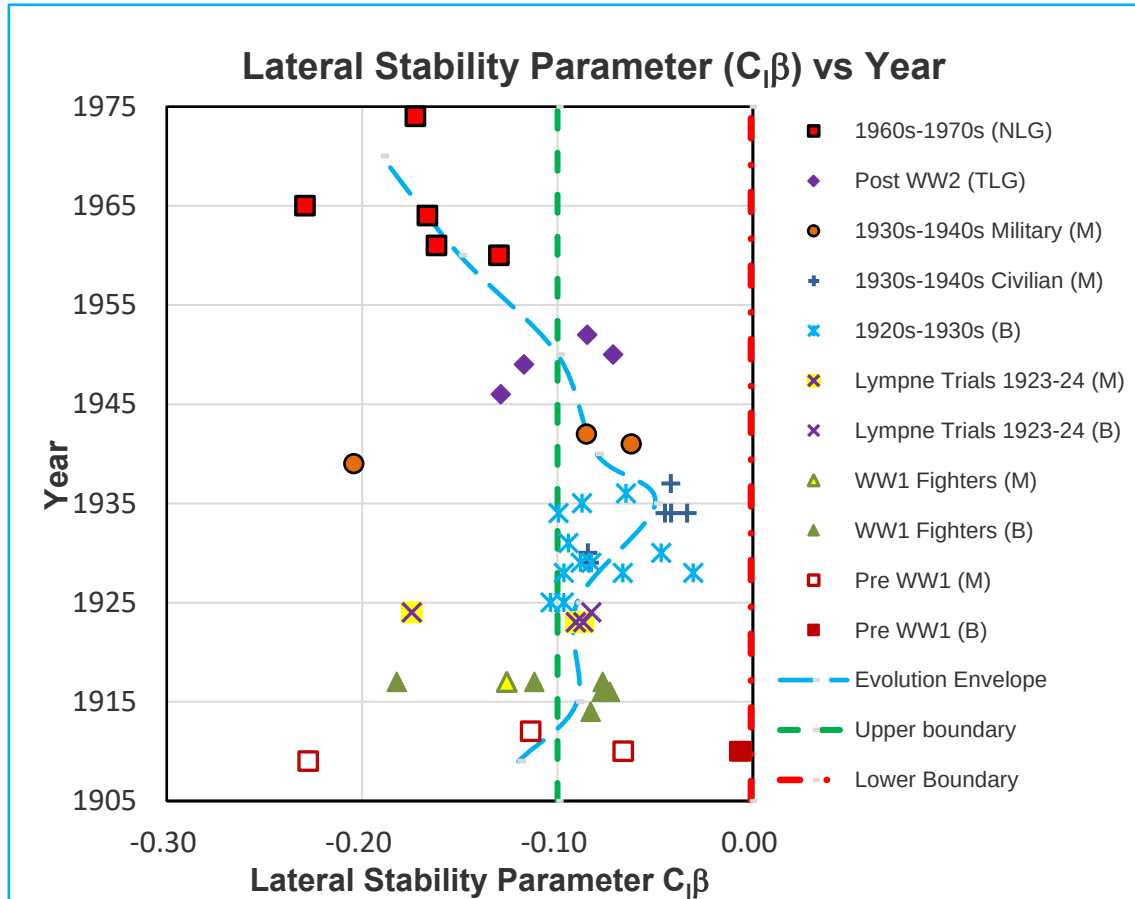


Figure 3-26 - Lateral Stability Parameter versus Year

The data points in Figure 3-26 are grouped as indicated in the legend and if a path through the approximate centroid of each group is examined an indication of the evolution of dihedral effect over time is obtained. The Upper and Lower boundaries are taken from (Stinton, 1983, p. 456 Eq. 13-6)

The data points are scattered even within some groups, notably in the Pre WW1 group, the WW1 Fighters group and the immediate post WW1 Lympne Trials groups. The variation in the Pre WW1 group is indicative of the diversity of aircraft design thought prevailing at the time. For example, one school of thought

favoured flat turns using the rudder to steer like a boat and thereby avoid roll and the dreaded 'capsize' so dihedral effect was undesired, and often fixed fins were omitted better to facilitate rudder-only flat turns. (This was how most European protagonists had assumed aircraft should turn until the Wright Brothers demonstrated coordinated banked turns in France in 1908.) Another school of thought, perhaps having learned from the Wrights, recognised the value of banked turns but still used the rudder to steer in the desired direction allowing the dihedral effect to roll the aircraft into a banked turn, the angle of bank being cautiously adjusted using a lateral control such as wing warping or ailerons. This is the reverse of current practice in which the lateral control is used to roll the aircraft to the desired bank angle for the turn and the rudder used to prevent adverse yaw and balance⁹ the turn. These two philosophies resulted in aircraft in which the lateral and directional responses were very different. For example, in the case of the Bleriot XI to turn at low speed the rudder can be used to generate roll and bank through $C_l\beta$ rather than use the lateral control which can generate excessive adverse yaw – perhaps enough to neutralise roll power. Contrast this technique with that used on aircraft such as the Deperdussin and Avro Triplane which have no dihedral effect - with these aircraft the lateral control must be used to roll the aircraft into a bank, and the rudder must be held near neutral to turn with minimum sideslip.

By the time of the WW1 Fighters group, it was widely accepted in the UK that some degree of dihedral effect was desirable, for example, with $C_l\beta = -0.18$, the 1917 Royal Aircraft Factory SE5a was designed using all the available scientific knowledge of static stability almost regardless of complication and production cost – and a very good aircraft it was. In the Lymington Trials group the 1924 ANEC II ($C_l\beta = -0.17$) is an outlier due to its combination of high wing location and geometric dihedral, the others in the group being within the normal range. There is a significant range of dihedral effect in the 1920s-1930s group perhaps indicative of some of the pioneer designers' personal preferences. In the 1930s-

⁹ A balanced turn means a turn with no lateral acceleration remaining on the aircraft - also known as a co-ordinated turn.

1940s civilian monoplane group one sees the lowest levels of dihedral effect but three of the aircraft were designed specifically as racers in which other design considerations tended to predominate over static stability. The 1939 Westland Lysander ($C_{l\beta} = -0.204$) is the outlier in the military monoplane group due to its combination of high wing location and geometric dihedral. Except for the 1946 Anson ($C_{l\beta} = -0.13$), the Post WW2 group are within the typical range. It is notable that the 1960s-1970s aircraft have significantly higher levels of dihedral effect which probably reflects the introduction of formal airworthiness codes and requirements informed by the expansion of knowledge gained from extensive research during WW2. One of these airworthiness requirements is for the pilot to be able to retain attitude control and make a safe landing if any primary control becomes inoperative, thus it must be possible with an inoperative lateral control system to make safe turns to return to and land on an airfield using the rudder, sufficient $C_{L\beta}$ facilitates that.

3.4.2 Estimation of lateral control power

Using a similar analysis technique, it is possible to estimate Aileron Control Power ($\partial C_l / \partial \delta_A$ or $C_{l\delta_A}$). One method for estimating this parameter by quantifying equation 3-27.

$$\frac{\partial C_l}{\partial \delta_a} = \frac{2a_w \tau_A}{S_w b_w} \int_{k_1 \frac{b}{2}}^{k_2 \frac{b}{2}} cy \, dy \quad (3-27)$$

(Perkins & Hage, 1949, p. 354 Eq. 9-21)

Where 2 is the number of ailerons, a_w is wing lift curve slope, τ_A is aileron effectiveness parameter, S_w is wing area and b_w is wingspan. The integral limits refer to k_1 – the spanwise location of the inboard end of the aileron and k_2 the outboard end – these multiplied by the semi span ($b/2$). The final term calculates the moment from the product of: the spanwise width of the incremental strip (dy), the local chord (c), and its distance from the centreline (y). The aileron effectiveness parameter (τ_A) is a function of the ratio of aileron chord to wing chord ($C_A/\bar{c}_w$). The recommended range for $C_A/\bar{c}_w$ is 0.15 to 0.25 and is shown in

Figure 3-27 below with the values estimated for the aircraft in the study. The figure shows that the Pre WW1 group at 0.25 but this is because four of the five aircraft use wing-warping for lateral control and the aileron chord is assumed to be equivalent to 25% of wing chord. The WW1 Fighter, Lypmne Trials and 1920-1930s groups have average values of $C_A/\bar{c}_W$ around 0.35, thereafter all aircraft except for the Percival Provost fall within the accepted range.

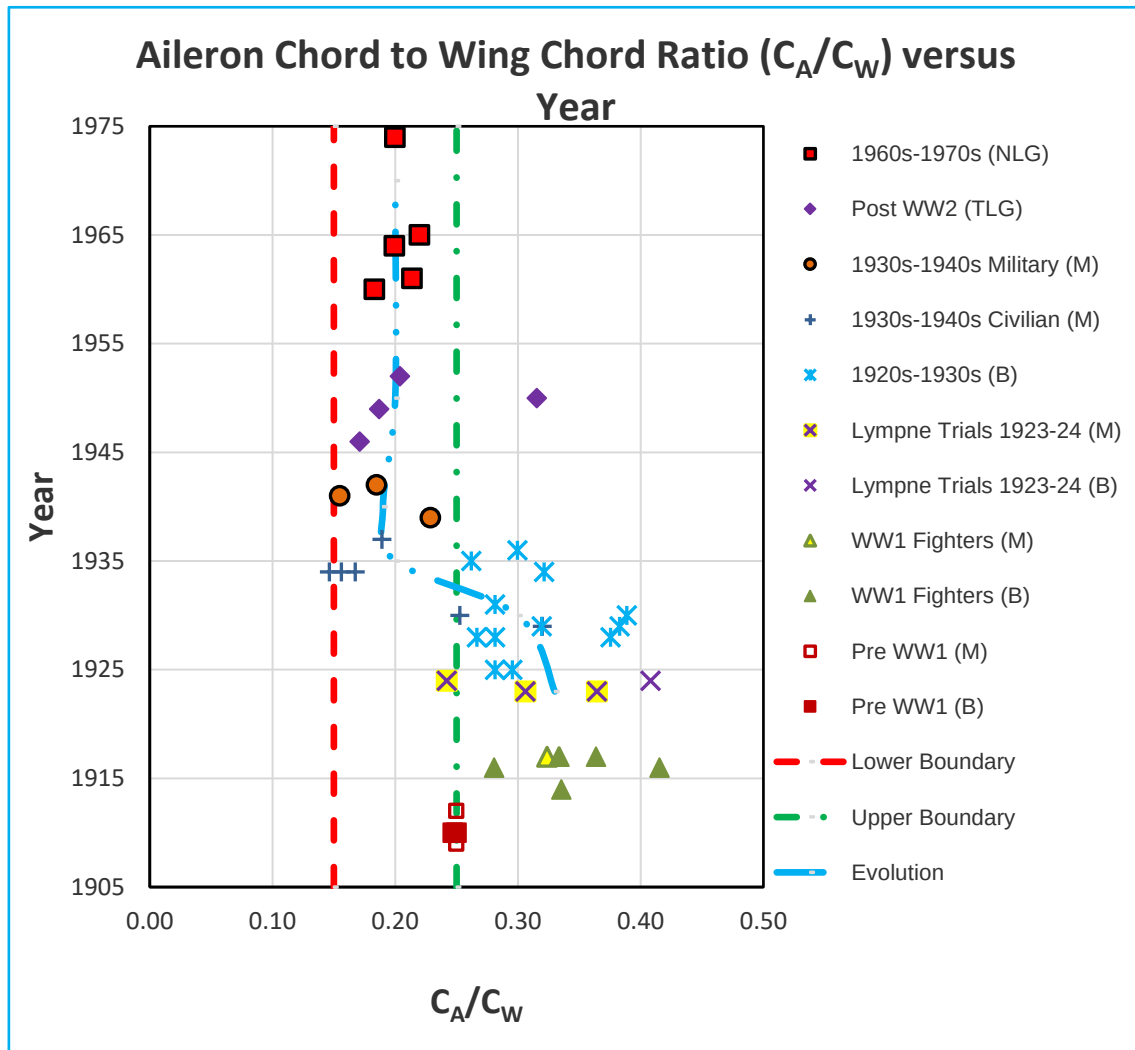


Figure 3-27 - Aileron to Wing Chords Ratio (C_A/C_W) versus Year

The relationship of τ_A to $C_A/\bar{c}_W$ was taken from (Dommasch et al., 1951, p. 495 Figure 15.19(b))

The original data from Dommasch was plotted and a curve fit used to establish a relationship between τ_A and $C_A/\bar{c}_W$ for use in the spreadsheet calculations. The

curve fit is considered acceptable between the range 0.15 and 0.4 for the purpose of this study.

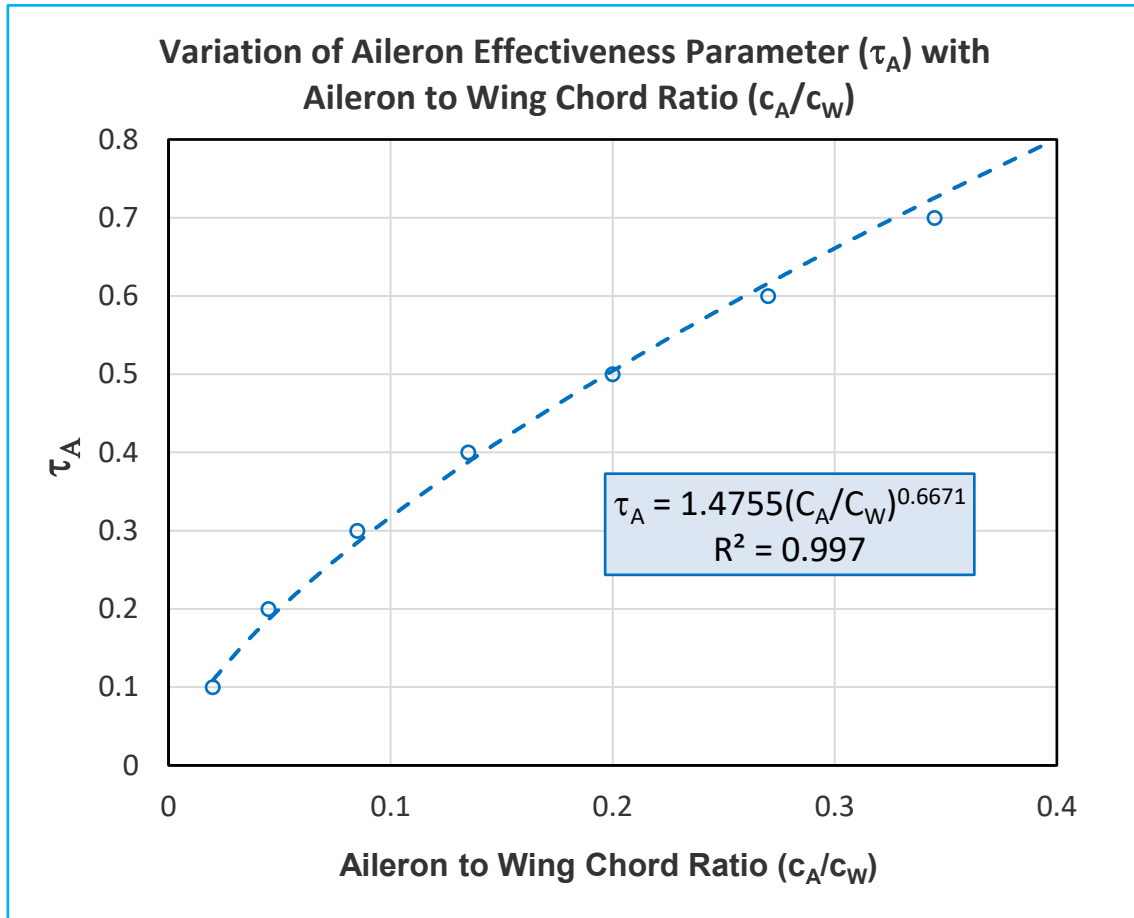


Figure 3-28 - Variation of Aileron Effectiveness Parameter (τ_A) with Aileron to Wing Chord ratio (C_A/C_W)

Using the geometric dimensions of the aircraft in the study the aileron effectiveness (τ_A) was derived from the c_A/c_W ratio and the equation of the curve fit in Figure 3-28. The values of τ_A for the subject aircraft are shown in Figure 3-29 which understandably follows a similar profile to that shown in Figure 3-27.

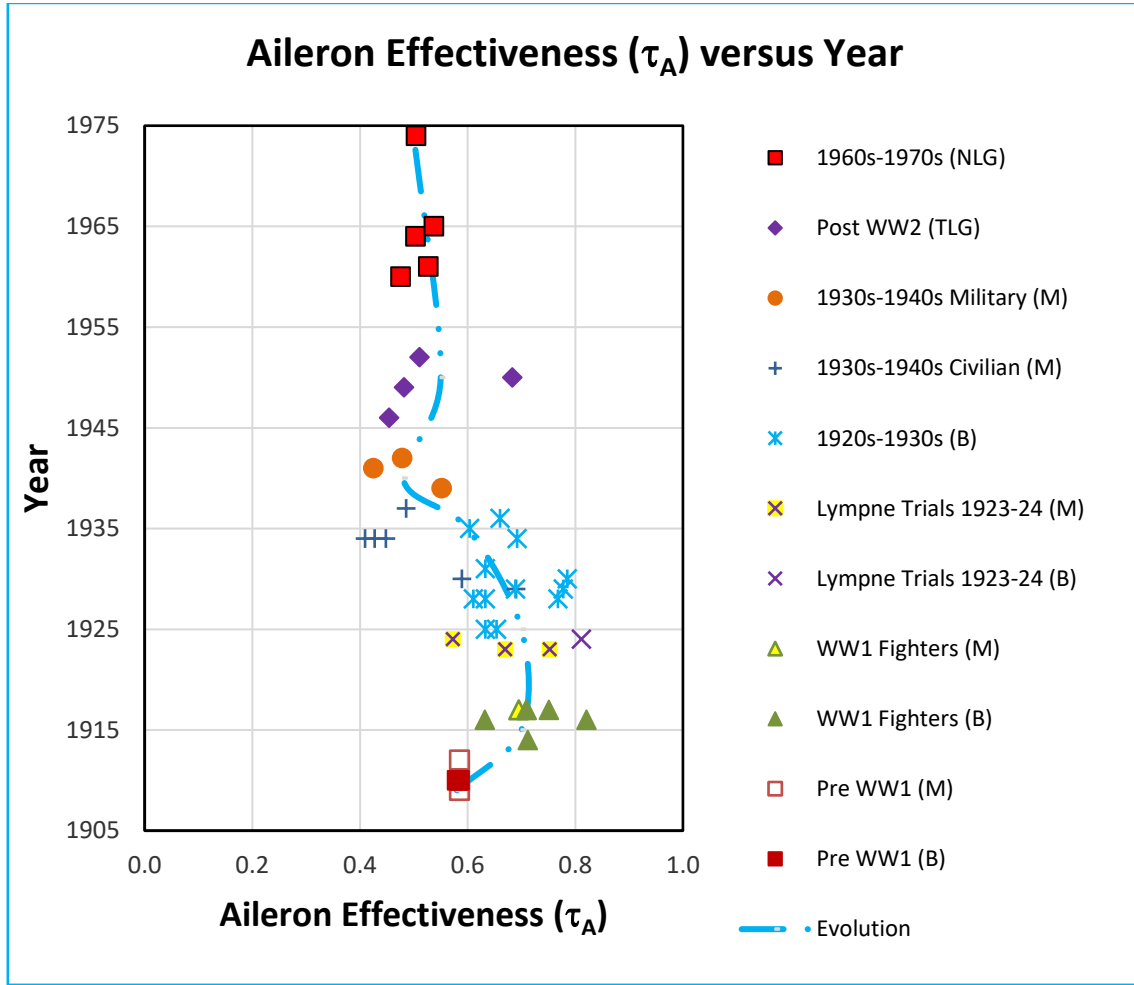


Figure 3-29 - Aileron Effectiveness (τ_A) versus Year

Another method to estimate aileron control power is found in Chapter 12 of (Sadraey, 2012 Eq. 12.12 & 12.23)

$$C_{l_{\delta A}} = \frac{2a_W \tau_A}{S_W b_W} \int_{y_1}^{y_0} C_y dy \quad (3-28)$$

Which for a tapered wing becomes

$$C_{l_{\delta A}} = \frac{2a_W \tau_A C_r}{S_W b_W} \left[\frac{y^2}{2} + \frac{2}{3} \left(\frac{\lambda - 1}{b_W} \right) y^3 \right] y_0 \text{ to } y_1 \quad (3-29)$$

Where C_r is the root chord and λ is the taper ratio.

A third method for estimating aileron control power was found by way of an on-line calculator which gives similar results to Sadraey. The equation for aileron

power found in United States Air Force Test Pilot School Flying Qualities handbook (Anon, 1986, p. 7.65 Eq. 7.81) and shown at equation 3-30, was investigated but discounted as it did not include τ_A , the aileron effectiveness parameter, and gave very different results to the other methods.

$$C_{\mathcal{L}}\delta_A = a_w \cdot \frac{\Sigma S_A}{S_w} \cdot \frac{y}{b_w} \quad (3-30)$$

Before examining lateral control power further, it is helpful to investigate Aileron Volume Coefficient. Aileron volume is the product of the total aileron area (ΣS_A) and the length of the moment arm (l_A) from the aircraft's plane of symmetry to the spanwise location of the centre of lift of the wing panel affected by the ailerons. To convert this to Aileron Volume Coefficient ($\bar{V}_A$) the aileron volume is divided by the product of wing area and wingspan ($S_w \cdot b_w$).

$$\bar{V}_A = \frac{\Sigma S_A \cdot l_A}{S_w \cdot b_w} \quad (3-31)$$

$\bar{V}_A$ is plotted versus year of aircraft manufacture in Figure 3-30.

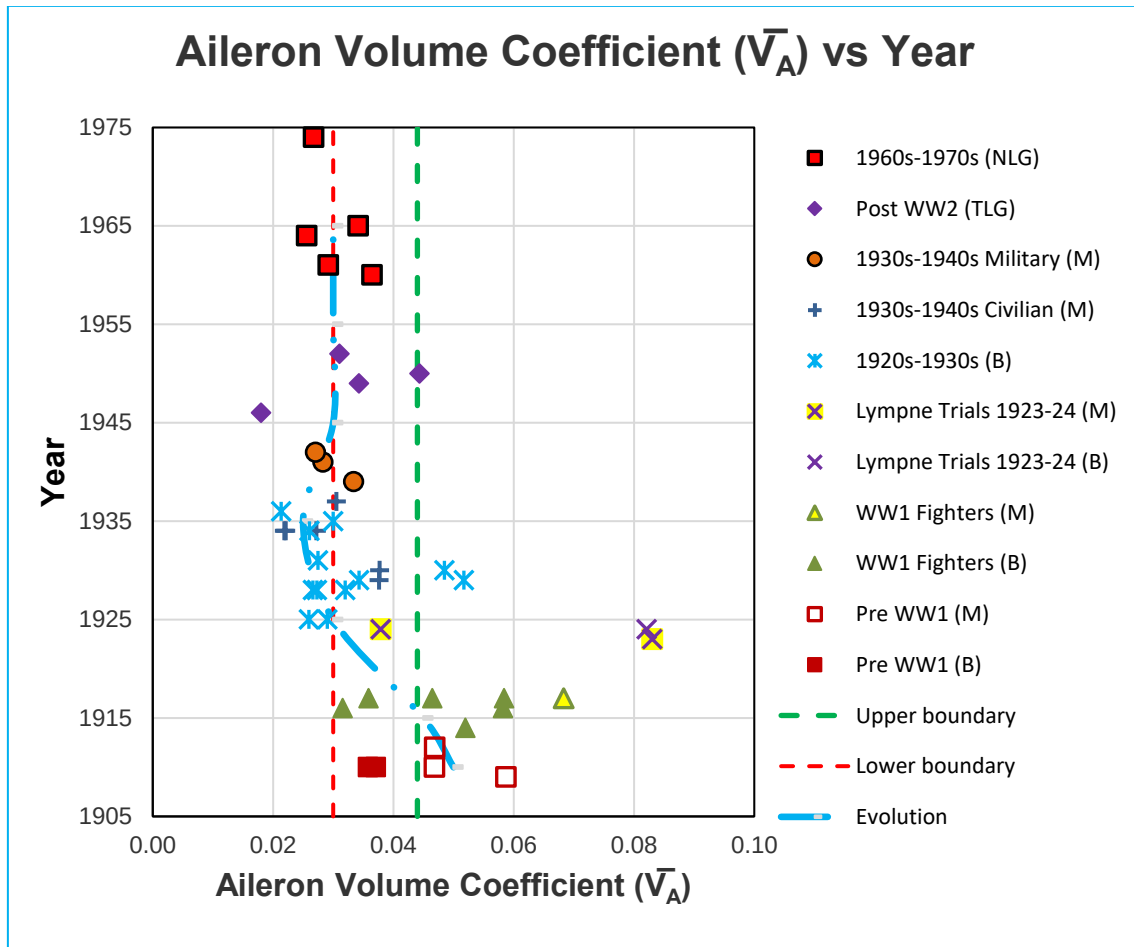


Figure 3-30 - Aileron Volume Coefficient versus Year of Manufacture

The Upper and Lower boundaries of $\bar{V}_A$ are taken from (Stinton, 1983, p. 455)

This shows that the value of Aileron Volume Coefficient varied considerably during the very early years. The 1923 and 1924 outliers are the English Electric Wren and Hawker Cygnet respectively both of which have very large area ailerons. From around 1925 onwards the average value of the parameter stays close to the recommended lower boundary.

Taking the same approach as that used in the longitudinal and directional cases it is helpful to examine the product of $\bar{V}_A$ and the dynamic pressure that the ailerons are working in; near the stalling speed (V_S) and at the maximum level flight speed (V_H).

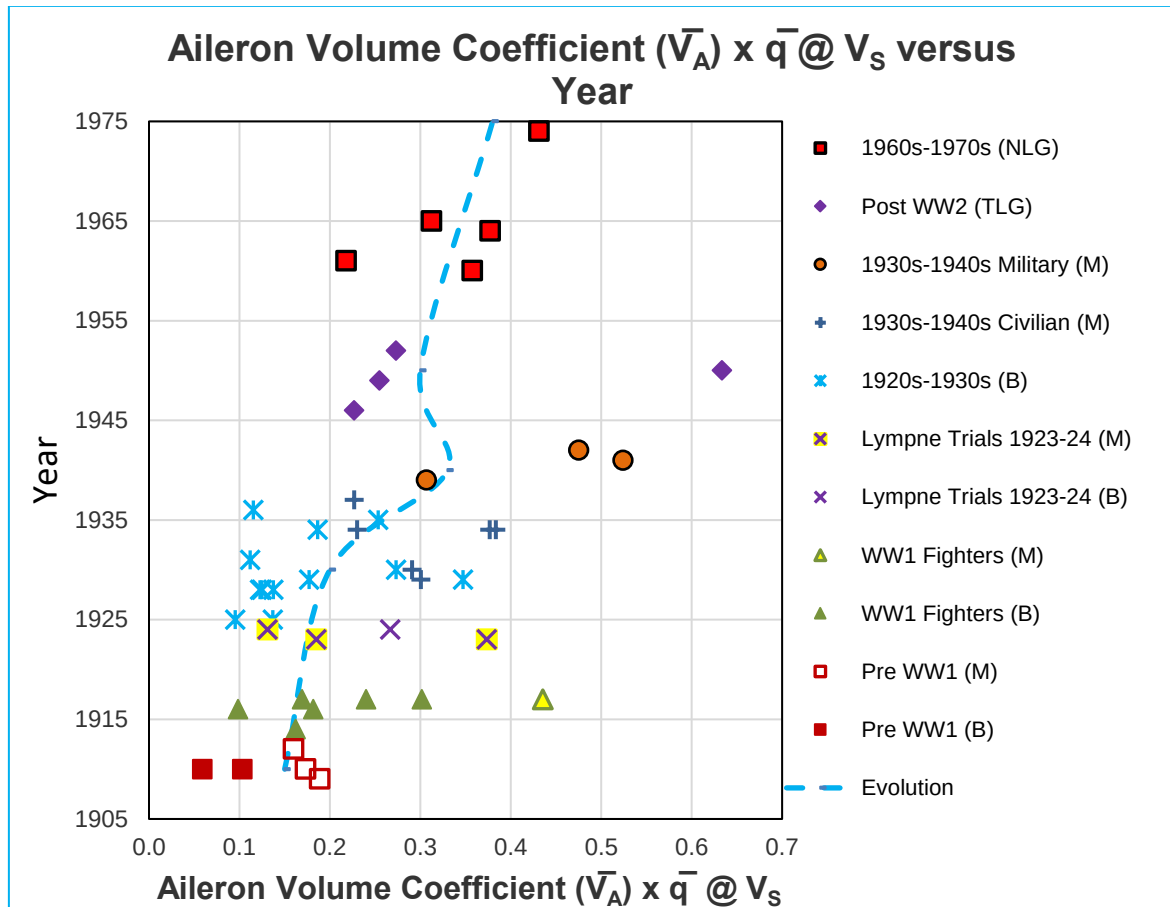


Figure 3-31 - Aileron Volume Coefficient x $\bar{q}$ at V_s versus Year

Figure 3-31 the evolution shows an increase as time advances, and this is driven by a corresponding increase in stalling speed. It is worth commenting on the more obvious outliers such as the 1917 Bristol M1c at 0.44 which, as a monoplane, has a wing loading of 9.2 lb/sq.ft. which is nearly double that of the other aircraft in the WW1 Fighters sub-group. The outlier in 1923 is the English Electric Wren mentioned in the discussion of Figure 3-30. The two outliers around 1940 are the Hawker Hurricane Mk1 and the Vickers Supermarine Spitfire Mk V which, as high-speed interceptors, have high wing loadings of around 25 lb/sq.ft. with associated high stalling speeds. The outlier in 1950 is the Percival Provost TMk1, a military trainer, which has a wing loading of 20 lb/sq.ft. and one of the highest values of aileron to wing area ratios – both parameters contributing to the relatively high value of $\bar{V}_A \bar{q}$.

Figure 3-32 shows the value of $\bar{V}_A \bar{q}$ at maximum level speed (V_H) and the evolution shows a sharp increase for the WW1 fighters (4 ailerons) then halving in value in the 1920s (two ailerons) and thereafter a steady increase over time. There are with three additional outliers compared with Figure 3-31; these being the 1934 DH-88 Comet Racer, the 1935 Gloster Gladiator Mk1 interceptor, and the 1939 Westland Lysander, a RAF army cooperation aircraft all just over 3 units and all three being relatively high-speed machines which explains the high values of $\bar{V}_A \bar{q}$ at V_H .

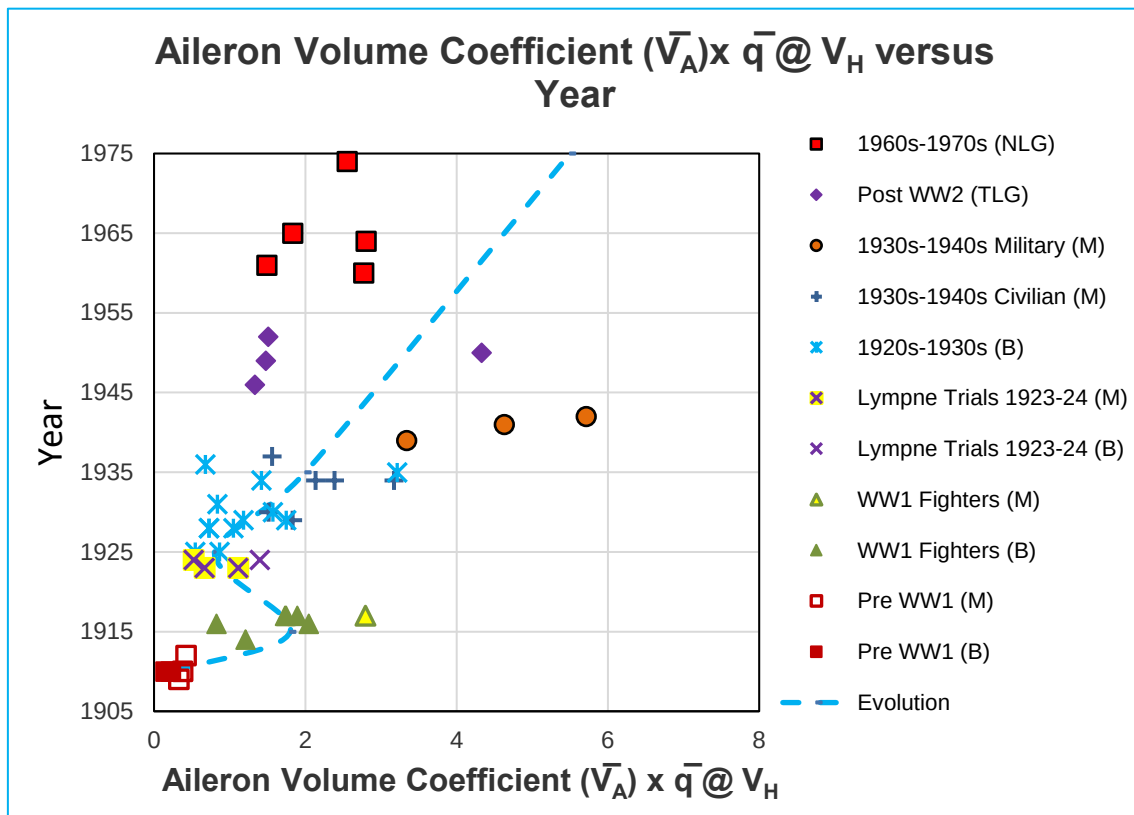


Figure 3-32 - Aileron Volume Coefficient x $\bar{q}$ at V_H versus Year

Lateral Control Power ($C_{l\delta_A}$) for the subject aircraft was calculated using equation 3-26. The value of $C_{l\delta_A}$ and its evolution over the period of study is shown in Figure 3-33.

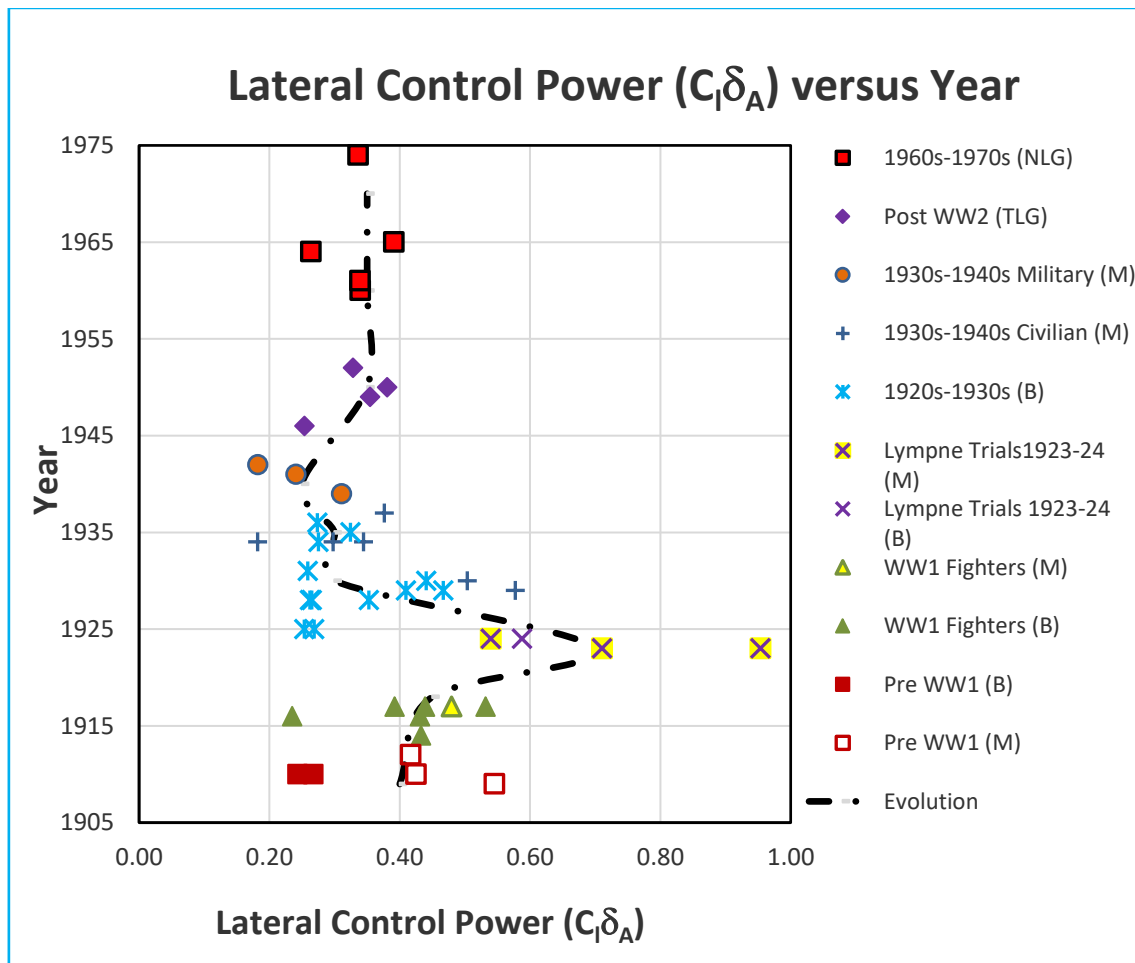


Figure 3-33 - Lateral Control Power vs Year

In the Pre WW1 group, the monoplanes show higher values but these aircraft use ‘wing-warping’ for lateral control. With this mechanisation differential lift is achieved by twisting the wings asymmetrically – the rear spar is usually hinged at the root fitting to allow it to be moved up or down by wires from the pilot’s control inceptor. Assuming a rigid front spar, pulling the rear spar upwards will reduce the wing angle of attack while on the opposite wing pulling the rear spar downwards will increase the wing angle of attack – the resulting differential lift giving rise to a rolling moment. This system was superseded by ailerons for several reasons, but key was that warping required the wing structure to be flexible which was not compatible with going faster due to aeroelastic considerations such as divergence, control reversal and flutter. But, for the essentially single-speed machines of this period, it was adequate but could produce significant adverse yaw. In this study, wing warping posed a problem in

defining Lateral Control Power since that parameter needs aileron dimensions and location as inputs. Since there can be no discrete ‘control’ area or arm with the warp system it was decided to define an equivalent aileron area as being equal to the product of, the quarter wingspan ($b/4$) and a quarter chord ($c/4$) and the spanwise centroid at half assumed aileron span ($b_A/2$). ¹⁰This arbitrary approach cannot be entirely representative and so the absolute values of $C_l\delta_A$ for these four aircraft must be treated with caution but comparisons within this subgroup should remain valid. The WW1 biplane Fighters all enjoy high values around -0.45 (due to having four ailerons) although there is an outlier, the Sopwith Pup at -0.23 which had four ailerons but with lower aileron volume.

The Lympne Trials aircraft of 1923-24 are clearly outliers and this is driven by large aileron to wing area ratios. These aircraft were designed specifically to participate in the 1923-24 light aircraft competitions and points were awarded for speed range which involved flying at the minimum possible speed. The minimum speeds of these aircraft were 25-30 knots so, given the competition requirement to demonstrate these speeds at low altitude, the designers had to ensure adequate lateral control performance by significantly increasing aileron areas. Because of this design feature these aircraft should be considered to be atypical with respect to lateral control characteristics.

Between about 1925 and 1935 there appears to be much scatter. Thereafter the parameter settles at an average of around -0.35.

3.4.3 Estimation of rolling moment due to yaw rate

The third term in equation 3-23 is rolling moment due to yaw rate (C_{lr}) previously mentioned in Chapter 5. This rolling moment is generated from the different airspeeds experienced by advancing and retreating wings causing asymmetrical lift when an aircraft yaws about its z axis. In this context yaw rate could be that

¹⁰ When making surface and control measurements on the aircraft in the study with wing warping lateral control it was found that when using that accepted lateral force on the inceptor only a small area of the wing moved. This was assessed as being approximately equivalent to the outer $b/4$ spanwise and rearmost $c/4$ chordwise.

generated by a rapid rotation about the z axis or the relatively slow rates of yaw about that axis that are experienced during normal turning flight.

Various equations for estimating rolling moment due to yaw rate were examined. In Perkins & Hage (1949) and in Dommasch et al. (1951) these equations are simplified to

$$C_{l_r} = \frac{C_L}{4} \quad (3-32)$$

In Flight Dynamics Principles (Cook, 2007, p. 368 Eq. 13.151) the approximation is given as $C_L/6$. For this study both approximations were examined and the value of lift coefficient selected to derive C_{l_r} was that C_L pertaining at an airspeed midway between V_S and V_H . Although demonstrably a function of C_L , intuitively it is the speed differential between the wings that results in an asymmetric lift distribution which creates the roll moment. A plot of the derived values of C_{l_r} ($= C_L/4$ and $= C_L/6$) versus the median airspeed in knots as shown in Figure 3-34. This shows $C_{l_r} = C_L/6$ for the subgroups of the aircraft in the study as indicated in the legend and also where $C_{l_r} = C_L/4$ for all the aircraft in the study presented as one data set.

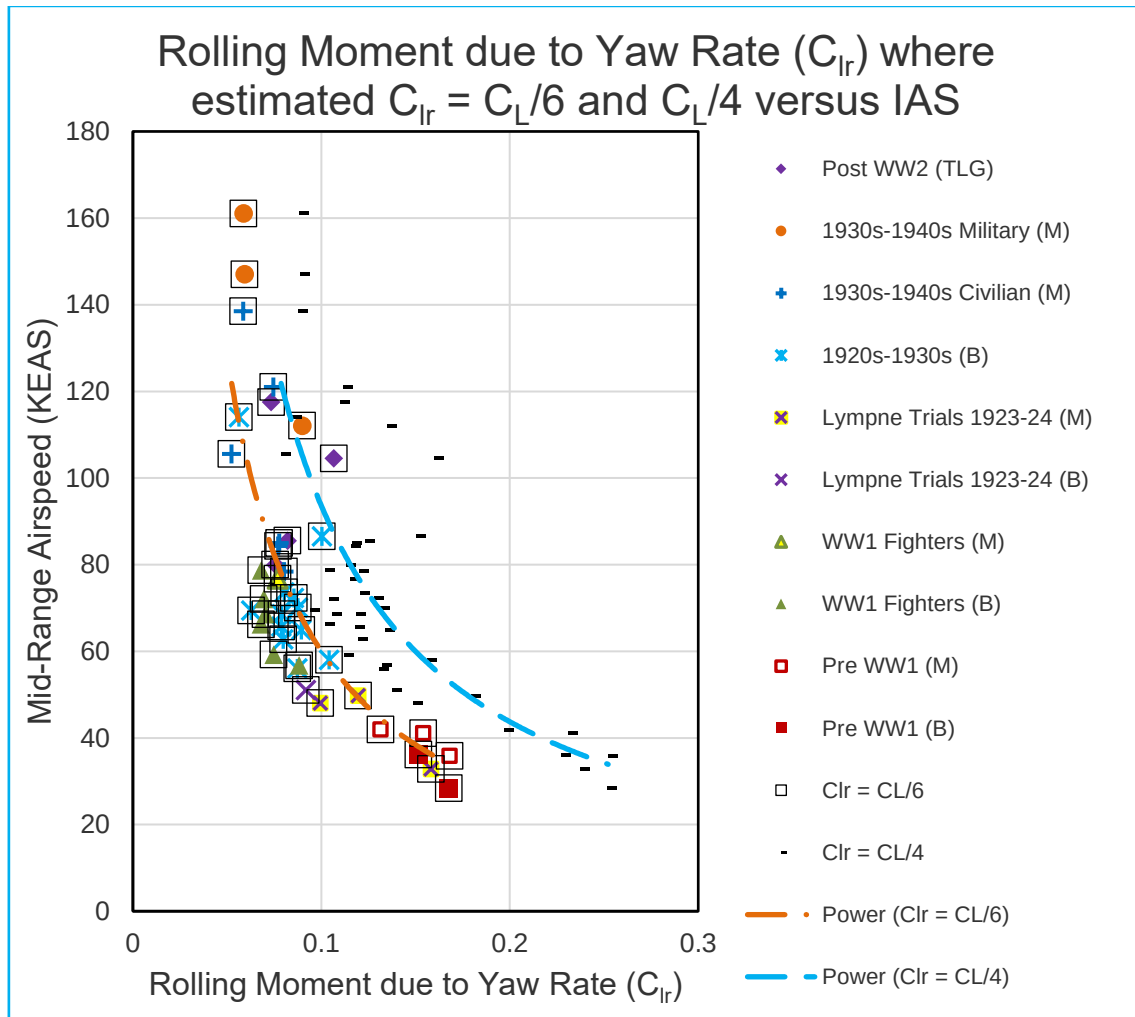


Figure 3-34 - Rolling Moment due to Yaw Rate versus Airspeed

This also indicates an inverse relationship between C_{lr} and airspeed with the highest values of C_{lr} at the low airspeeds associated with the Pre WW1 and Lympne Trials aircraft, but the effect is halved at 70 kt and lower still at 100 kt. This illustrates that it is a relatively minor effect during turns in faster post- WW2 monoplanes but is a significant parameter, which may require moderate pilot compensation, when flying low-speed aircraft.

3.4.4 Estimation of rolling moment due to roll rate – roll damping

Another of the contributions to the overall aircraft rolling moment expressed in equation 3-23 is rolling moment due to roll rate (p) which is known as ‘roll damping’ and in coefficient form is expressed as C_{lp} . The value of C_{lp} as a function of Aspect Ratio (A) and Taper Ratio (λ) was derived from extensive NACA flight

test results published in NACA Report 635 and reproduced in (Perkins & Hage, 1949, p. 357 Figure 9-14)

The relationship is expressed as a graph in Figure 3-35.

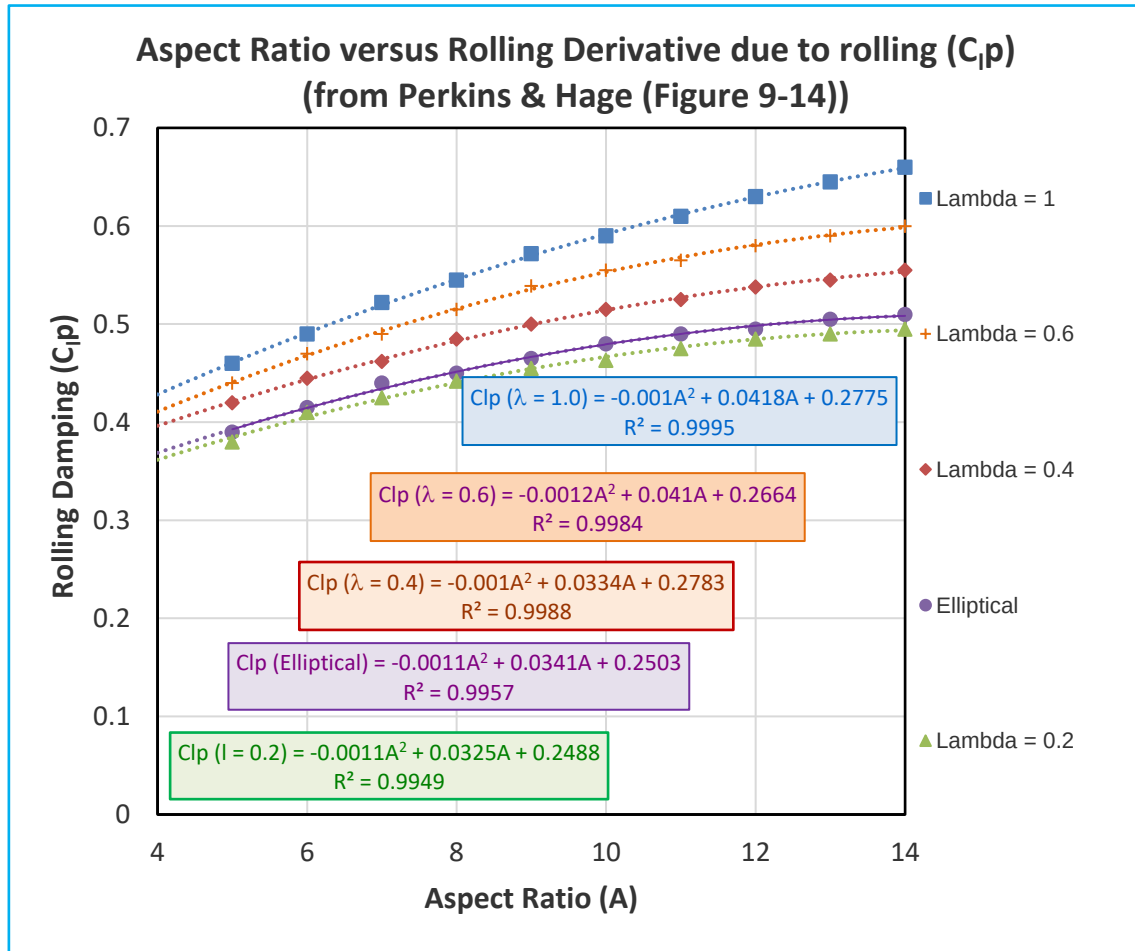


Figure 3-35 - Variation of Roll Damping Parameter (C_{lp}) with Aspect Ratio (A) and Taper Ratio (λ)

Aircraft in the study group have aspect ratios between 4 and 10; none of the biplanes have wing taper; the taper ratios of the monoplanes in the sample range from 0.8 (Desoutter) to 0.17 (DH-88). The curve fits between $A=5$ and $A=10$ appear to be good, so the equations of the lines were used in the spreadsheet to derive C_{lp} .

The derived Roll Damping parameter was plotted against Roll Control Power as shown in Figure 3-36 which shows a tight grouping suggesting a relation of close to 1:1 for these parameters. The two data points with very high roll power are

from the Lympne Trials group which, as discussed above, had over-large ailerons to give adequate control power at very low airspeeds.

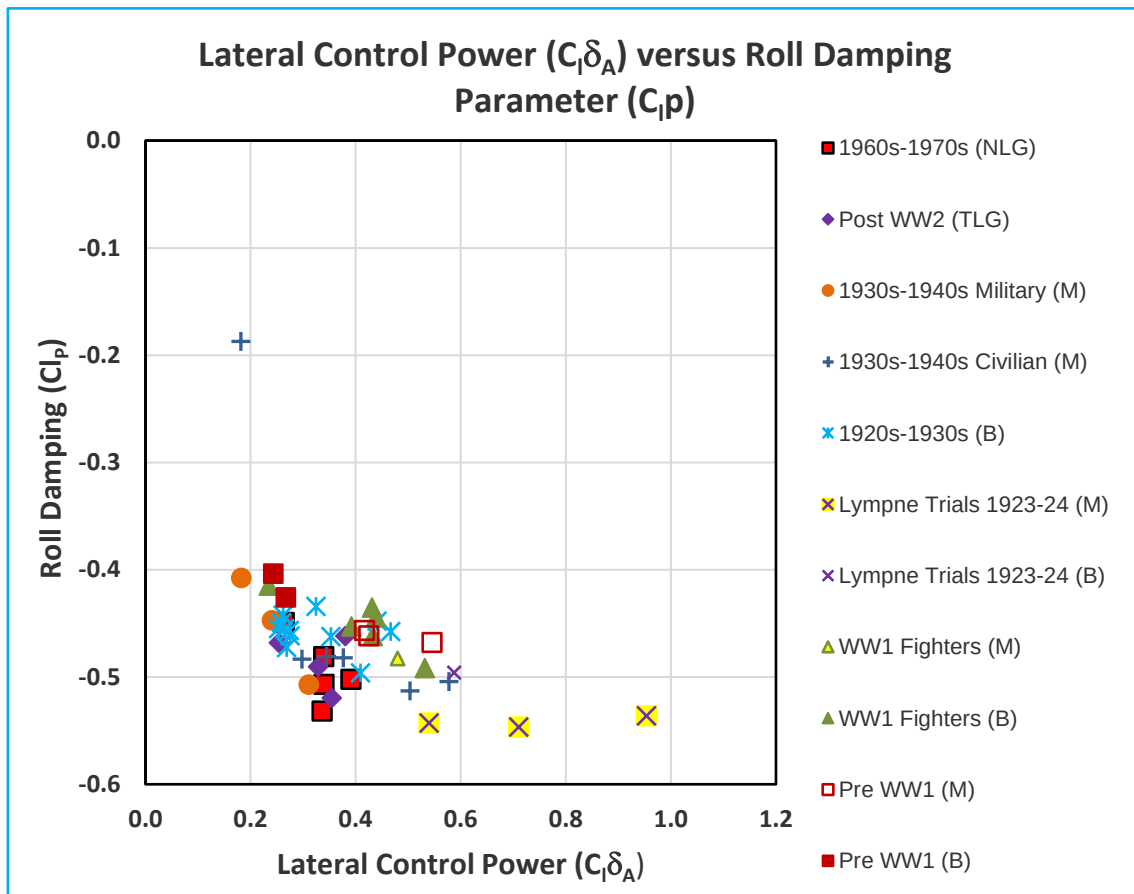


Figure 3-36 - Lateral Control Power ($C_l\delta_A$) versus Roll Damping (C_{lp})

The roll mode time constant describes how quickly the aircraft achieves a steady rate of roll for a given aileron deflection. It is a fast subsidence in roll acceleration and only adversely affects handling qualities if it is excessively slow. It is a function of the moment of inertia in roll (I_{xx}) and the roll damping parameter (C_{lp}), which in turn is a function of aspect ratio (A) and taper ratio (λ). A plot of C_{lp} versus estimated I_{xx} is shown in Figure 3-37 which shows that C_{lp} lies between -0.4 and -0.55 for all the aircraft in the study group except the 1934 Comet racer in which C_{lp} is -0.187 due to its tapered wing planform ($\lambda = 0.2$). It is reasonable to assume that the roll mode time constant will increase with increasing I_{xx} and reducing C_{lp} but only in the Comet ($C_{lp} = -0.187$) and the relatively large Anson, with $I_{xx} = 12700$, is it likely to be noticeable to the pilot.

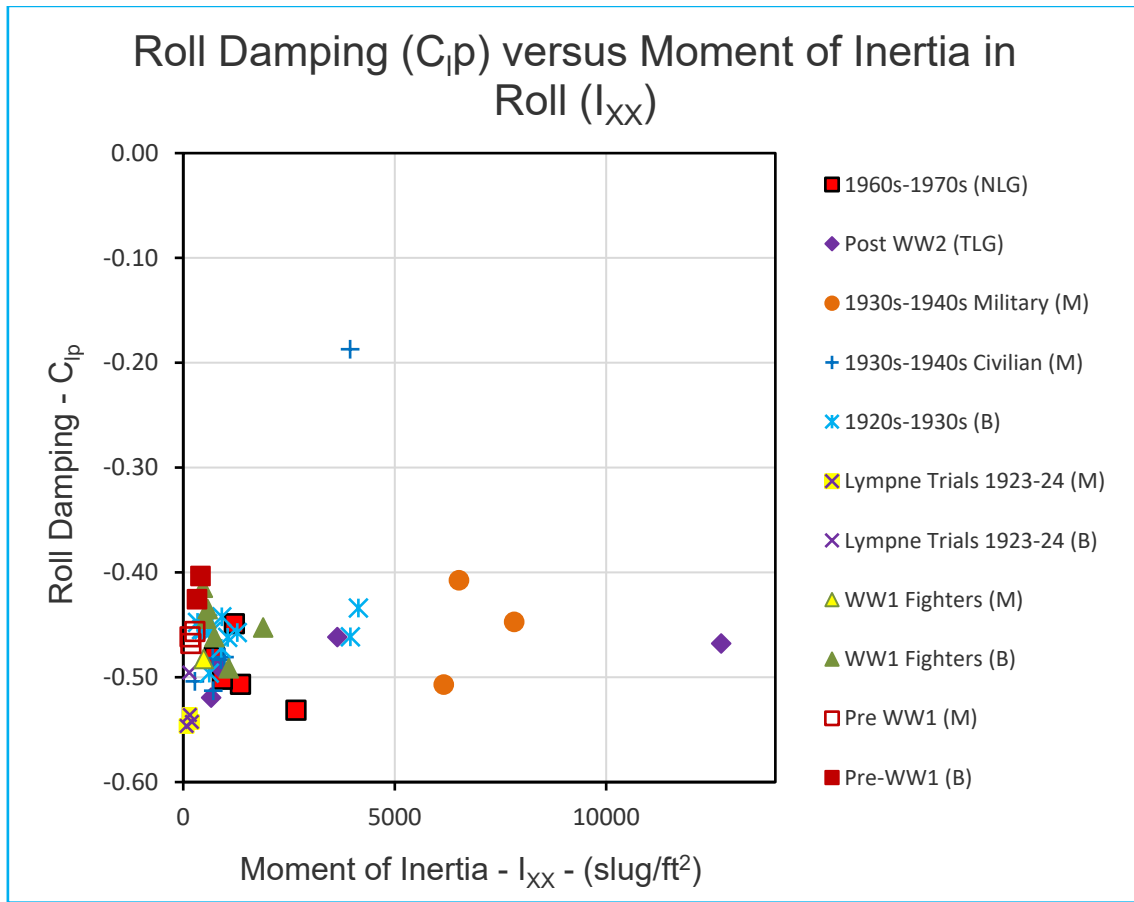


Figure 3-37 - Moment of Inertia in Roll (I_{xx}) versus Roll Damping (C_{lp})

3.4.5 Estimation of the spiral criteria

The spiral mode describes the time history in roll angle following a disturbance in roll angle. If the roll angle tends to return towards wings level the spiral mode is said to be stable, if it diverges further, it is unstable. Usually this is a small effect and easily corrected by the pilot even when it is unstable but, in the early days of powered flight in aircraft deficient in roll control power and/or deficient in dihedral effect this may have contributed to many accidents. The spiral mode is stable if the product of $C_{l\beta}$ (dihedral effect) and C_{nr} (yaw damping) is greater than the product of $C_{n\beta}$ (weathercock stability) and C_{lr} (roll due to yaw rate). Figure 3-38 shows the Spiral Criteria (where greater than zero indicates stability) for the aircraft in the study group.

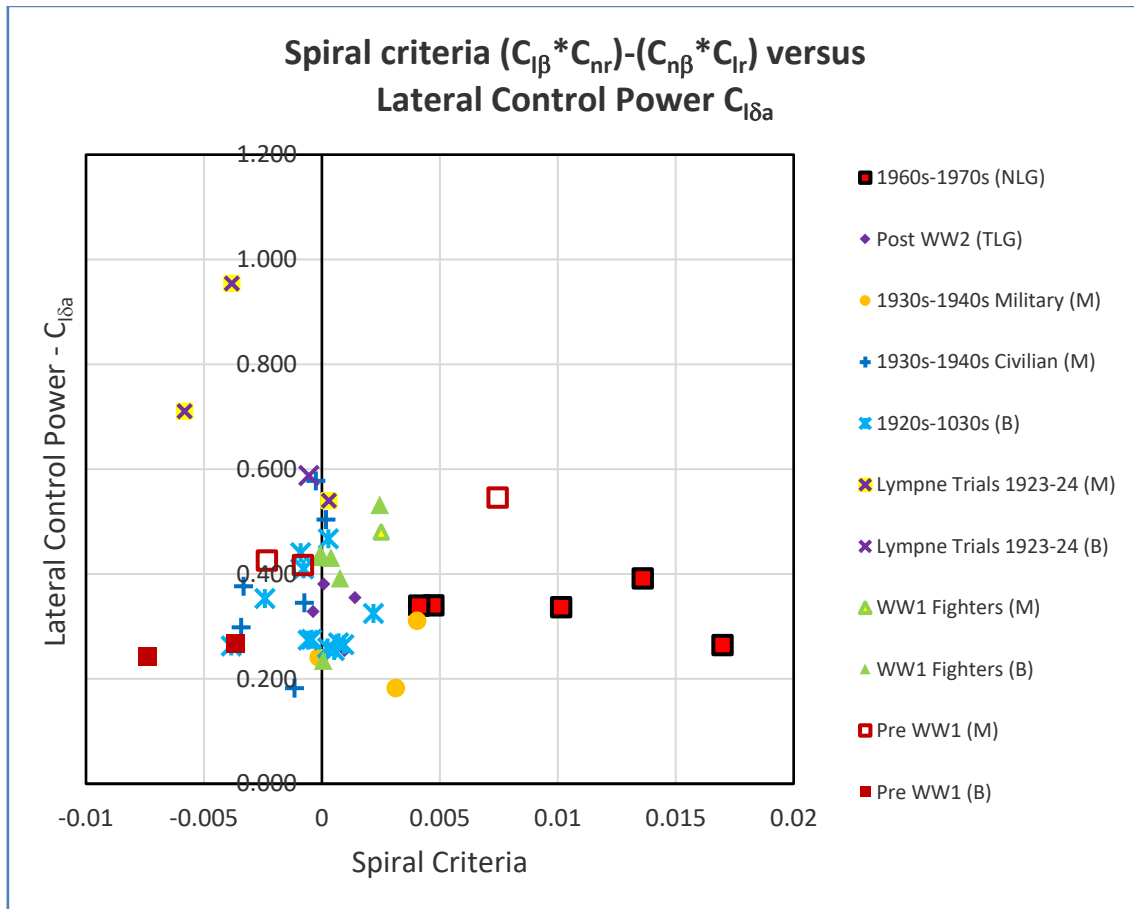


Figure 3-38 - Spiral Criteria versus Lateral Control Power

Figure 3-38 shows that the majority of vintage aircraft are tightly grouped between $C_{l\delta a}$ 0.2 to 0.6 and the spiral criteria between -0.004 and +0.004. With the exception of the 1909 Bleriot (which has generous dihedral) all the Pre WW1 aircraft have unstable spiral criteria and two have relatively low lateral control power which is a potentially dangerous combination. Two of the Lypmne Trials monoplanes also show unstable spiral criteria nut coupled with high lateral control power and this combination is acceptable. The aircraft in the 1960s-1970s group all have moderate lateral control power and much higher positive values of spiral criteria facilitating more benign handling especially when flying on instruments.

The legacy requirements such as BCARs (British Civil Airworthiness Requirements - Section D, 1981, pp. D2-8) placed a limit on spiral divergence in the initial climb, namely that from a 20° banked turn the aircraft should not increase bank to 40° in less than 10 seconds, while in (Military Specification -

Flying Qualities of Piloted Airplanes, 1980) the time for the same bank angle change is 12 seconds for Level 1 handling. These requirements allow an into-turn roll rate of 1.7 to 2.0°/second which will be a distraction to the pilot requiring moderate compensation. This regulatory acceptance of an instability in roll may be symptomatic of a compromise, necessary in un-augmented aircraft, which lack any form of stability augmentation, to avoid adverse Dutch roll characteristics.

3.5 Cross coupling

The analysis in paragraph 3.2 assumes that the longitudinal axis can be examined in isolation, i.e., it is not significantly affected by the directional and lateral stability and control characteristics and that is broadly correct. However, the lift on the horizontal stabiliser can be affected when an aircraft sideslips causing a pitching moment and a pitch upset may result from a precession torque arising when a rotating propeller/engine is yawed. Although in paragraphs 3.3 and 3.4 the directional and lateral characteristics have also been treated in isolation in the first instance, several stability and control derivatives contain both directional and lateral characteristics. Rolling moment due to sideslip (dihedral effect) and rolling moment due to yaw rate have already been introduced in paragraphs 3.4.1 and 3.4.3. The yaw axis may be affected by propeller effects such as 'P' factor (asymmetric blade effect) and the precession torque arising when a rotating propeller/engine is subject to a pitching motion. The roll axis will be affected by engine/propeller torque. Both yaw and roll axes are affected by the spiral propeller slipstream, the asymmetry of which alters the angle of sideslip sensed by the fin and in some cases the angle of attack differently on each wing. The more powerful the propeller power plant the greater these effects are.

3.5.1 Engine/propeller gyroscopic precession

The engine and propeller take on the properties of a gyroscope when rotating and especially so when the entire engine spins with the propeller as in the rotary engines in use between 1900 and 1920. Whenever the aircraft yaws it applies a torque to the spinning engine/propeller combination and the resulting precession outputs that torque back to the aircraft but through 90 degrees in the direction of

rotation. Thus, if an engine/propeller which rotates clockwise when viewed from the rear experiences a pitch up it will cause a yaw to the right. Similarly, if that engine/propeller experiences a yaw to the right it will cause the aircraft to pitch nose down. The magnitude of the effect is a function of; the angular rate, the rotational speed of the engine/propeller, and the sum of the rotational moments of inertia of the engine and propeller. A rotational moment of inertia is a product of the mass of the rotating item and its radius of gyration. Therefore, as engine and propeller masses and diameters increase the effect becomes greater and, for any given engine/propeller combination, the effect is proportional to engine/propeller rotation speed. The effect it has on the aircraft is also a function of the moment of inertia of the aircraft itself and its static longitudinal and directional stability. The Sopwith Camel has a low moment of inertia and very low horizontal and vertical tail volume coefficients. Taking this aircraft as an example, a simple estimation of the moment that the small rudder can generate at different deflections was made using equation 3-33.

$$M_R = a_R \delta_R \frac{1}{2} \rho V^2 S_R l_R \quad (3-33)$$

Where a_R is the lift slope (taken as 0.04 per deg), δ_R is the rudder deflection, V is 100 ft/s (70 mph - a typical climbing speed), S_R is the rudder area (4.9 ft²) and l_R is the length of the arm from the rudder to the aircraft centre of gravity (12.9 ft). A plot of rudder deflection versus this estimated yawing moment, up to the maximum deflection of 30° is shown on the left half of Figure 3-39.

Five engines were investigated: the 50 HP Gnome, 80 HP Le Rhone, 110 HP Le Rhone, 130 HP Clerget, and 150 HP Bentley. The three more powerful engines were fitted to Sopwith Camels, the two lower power engines are included for illustration only. The precession torque generated due to an angular rate was estimated for the five engines and associated propellers using equation 3-34 from a method described in O’Gorman (1912)

$$\tau = \Omega_{EP} \cdot \omega_A \cdot I_{E+P} \quad (3-34)$$

Where Ω_{EP} is the rate of rotation of the engine/propeller, ϖ_A is the yaw (or pitch) rate of the aircraft, and I_{E+P} is the sum of the moments of inertia of the rotary engine and propeller respectively. O’Gorman determined the moment of inertia and radius of gyration of a 50 HP Gnome by experiment. For this study his results were then scaled up for the other four engine and propellers using their respective masses and diameters.

The right half of Figure 3-39 shows the torque (which will be applied to the airframe as a yawing moment) that is generated by angular rates of pitch encountered during steep turns and loops inter alia.

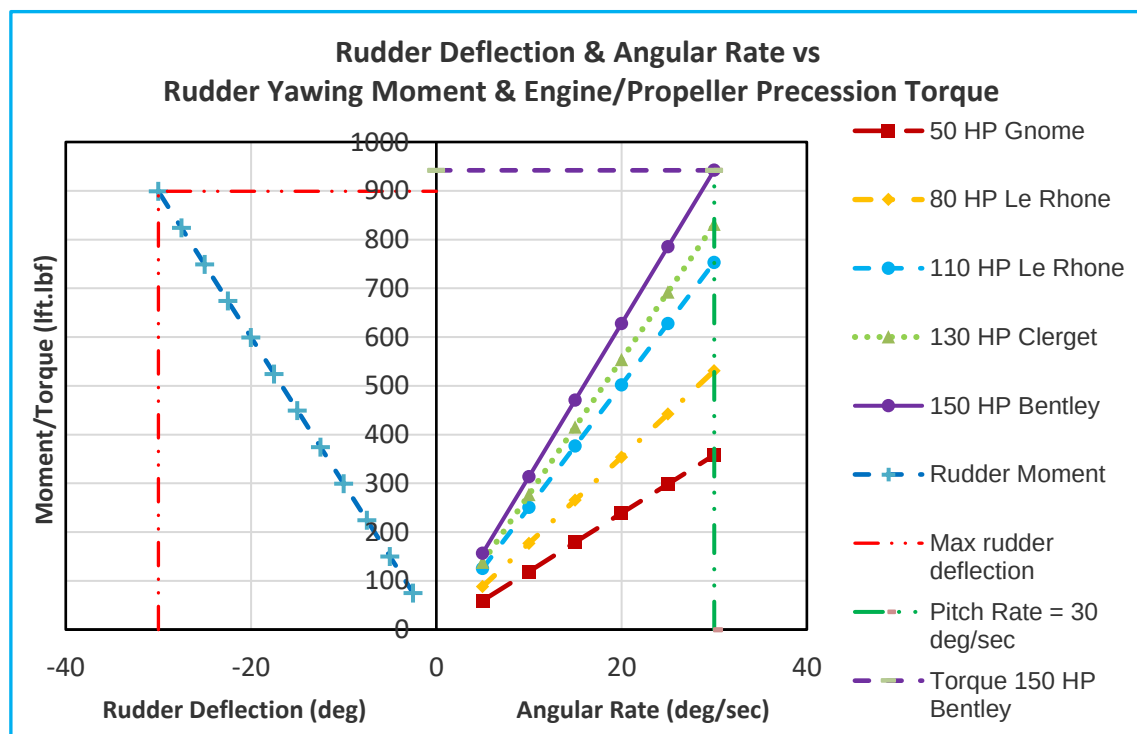


Figure 3-39 - Precession effects of rotary engines – Sopwith Camel

Assuming a high pitch rate of 30°/s, for the two low power engines the resulting yaw rate can be comfortably compensated for by the rudder, while for the 110 HP Le Rhone and the 130 HP Clerget the control margin is much reduced. However, the bigger 150 HP Bentley engine can develop more yawing torque due to a 30 deg/sec pitch rate than the rudder is capable of correcting, and this probably led to very high workload unless the pilot throttled back to reduce the RPM somewhat.

3.5.2 Adverse Yaw due to Aileron Deflection ($C_{n\delta a}$) and Roll Rate (C_{np})

Adverse (aileron) yaw ($C_{n\delta a}$) occurs when the ailerons are deflected. The down-going aileron generates more induced drag while the upgoing aileron generates less. The resulting difference in drag on each outer wing section causes a yawing moment in the opposite sense to the roll commanded by the aileron – hence the term ‘adverse yaw’. Adverse yaw due to roll rate (C_{np}) is caused once the aircraft starts to roll and due to the change in the angle of attack of each outer wing section the lift vectors are inclined forward on the downgoing wing and backward on the upgoing wing resulting in a yawing moment in the opposite sense to the commanded roll rate. At a given airspeed C_{np} is proportional to roll rate – so hardly noticeable at the low rates of roll associated with ‘normal’ flying but much more intrusive during the high rates of roll during aerobatics.

An approximation for the combination of these effects is given in (Dommasch et al., 1951, p. 500 Eq. 15:55) and shown in equation 3-35.

$$C_{N\delta_A} \sim \frac{C_L}{8} \frac{pb}{2V} \quad (3-35)$$

Where $C_L/8$ is the approximation and $pb/2V$ is the wing helix angle when the aircraft rolls around the longitudinal axis. To illustrate this parameter a roll rate of $p = 0.2$ radians/sec is assumed, V is a speed midway between V_S and V_H , the C_L is the lift coefficient at that speed; and b is the wingspan. This is plotted against the estimated lateral control power in Figure 3-40, which suggests that the Pre WW1 aircraft and the 1923-24 Lympne Trials aircraft are likely to have elevated levels of adverse yaw, whereas the remainder of the sample all show similar potential magnitudes.

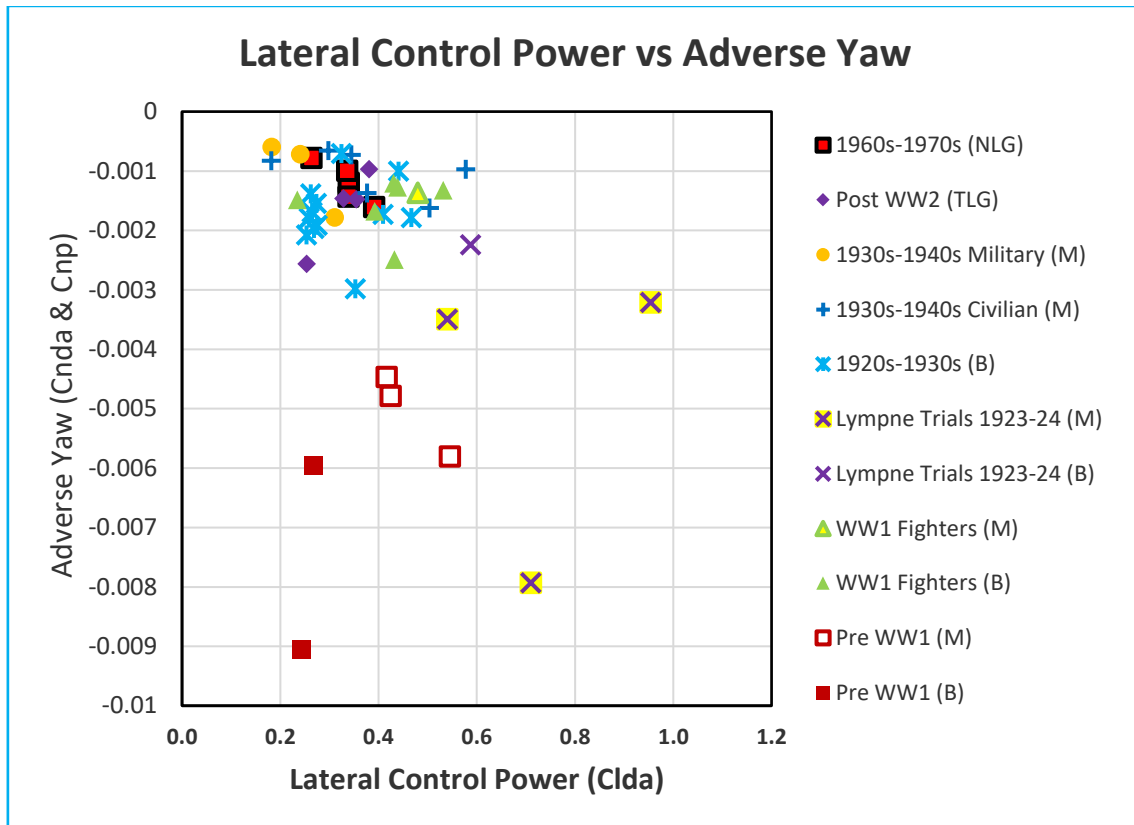


Figure 3-40 - Lateral Control Power ($C_{\delta A}$) vs Adverse Yaw ($C_{N\delta A}$)

The contribution to adverse yaw resulting from deflection of the aileron can be more or less compensated for by design features such as aileron nose shape (Frise), an aileron to rudder interconnect (ARI), or differential aileron gearing. Of these the first two are not found on the vintage aircraft in the study group but differential ailerons started to appear in British aircraft in the early to mid-1920s. Differential aileron gearing causes the down-going aileron to deflect less and the up-going aileron to deflect more so as to increase the drag on the up-going aileron and decrease drag on the down-going aileron. This is intended to minimise the asymmetry of the drag increments and thereby reduce the adverse yaw. However, it can be misleading to assume that because a vintage aircraft is equipped with differential ailerons that adverse aileron yaw will be absent. For example, the DH-82a, like several other contemporary De Havilland aircraft, is equipped with differential ailerons but they are singularly ineffective in helping to reduce adverse yaw in normal flying. However, it must be remembered that these aircraft were designed when turns were always initiated (and often maintained)

with the rudder, the ailerons playing the secondary role of adjusting the bank once the turn was established. Entering turns by leading with the rudder (a technique used mostly on gliders today) results in proverse yaw so a pilot using this (now archaic) technique will not experience adverse aileron yaw. The actual purpose of the De Havilland differential aileron system is described in a patent document, an extract of which is shown in Figure 3-41 (from the researcher's personal collection).

The DE HAVILLAND Patent DIFFERENTIAL AILERON CONTROL

IT being highly desirable to secure increased control round about stalling speeds, the De Havilland patent differential system was evolved to obtain much better and easier lateral control at all speeds, especially near stalling.

The system makes use of the fact that, throughout the flying range and more particularly at slow speeds, an upturned aileron gives better lateral control than a downturned one, and moreover up to a certain angle requires no effort to turn it up; it has, in fact, to be restrained by harnessing it to the opposite aileron which is being turned down. On the other hand, to turn an aileron down at stalling speeds requires an excessive effort with little or no increase of lift or lateral control. A very big drag, however, is introduced which, by slowing up the wing on that side of the machine and increasing the speed on the other, defeats the object which it is desired to attain and commences the swinging tendency experienced when near stalling, with its consequent side slip and spin.

Figure 3-41 - 'The De Havilland Patent Differential Aileron Control' extract

The text in Figure 3-41 shows that the primary purpose of the De Havilland differential aileron control was to '*obtain better control – especially near stalling*'. More importantly to avoid the aircraft entering a spin if the pilot attempted to use aileron to stop a wing dropping at the stall. Between neutral lateral stick and half deflection, the movements are conventional but between half and full deflection the down-going aileron returns to neutral while further increasing the deflection of the upgoing aileron. This is believed to be De Havilland's in-house attempt at reducing the high stall/spin accident rate prevailing at that time.

3.5.3 Lateral Control Departure Parameter (LCDP)

'The lateral control departure parameter predicts at what angle of attack roll reversal is expected to occur when using aileron. Reversal in this sense does not mean aeroelastic aileron reversal, but that condition where the rolling moment due to sideslip, resulting from adverse yaw, overpowers the rolling moment commanded by the ailerons.' USAF TPS FQ Handbook(Anon, 1986)

This parameter can be a feature of post WW2 swept-wing tactical aircraft such as the Corsair II but can apply to any aircraft with the necessary combination of stability and control derivatives.

$$LCDP = C_N\beta - \frac{C_N\delta_A}{C_l\delta_A} \cdot C_l\beta \quad (3-36)$$

By inspection of the equation the greater the adverse yaw ($C_N\delta_A$) and the rolling moment due to sideslip ($C_l\beta$) the more prone the aircraft is. Equation 3-36 is used to estimate the parameter for the aircraft of the study group and the results are shown in Figure 3-42. This suggests that the 1909 Bleriot XI is the worst case, the 1914 Avro 504K is also prone. The data points for 1910 Avro Triplane and Bristol Boxkite and the 1924 Hawker Cygnet also show LCDP = 0 but these aircraft have no fixed fin and no dihedral ($C_l\beta = 0$) so are the result of a multiplication by zero and can be ignored.

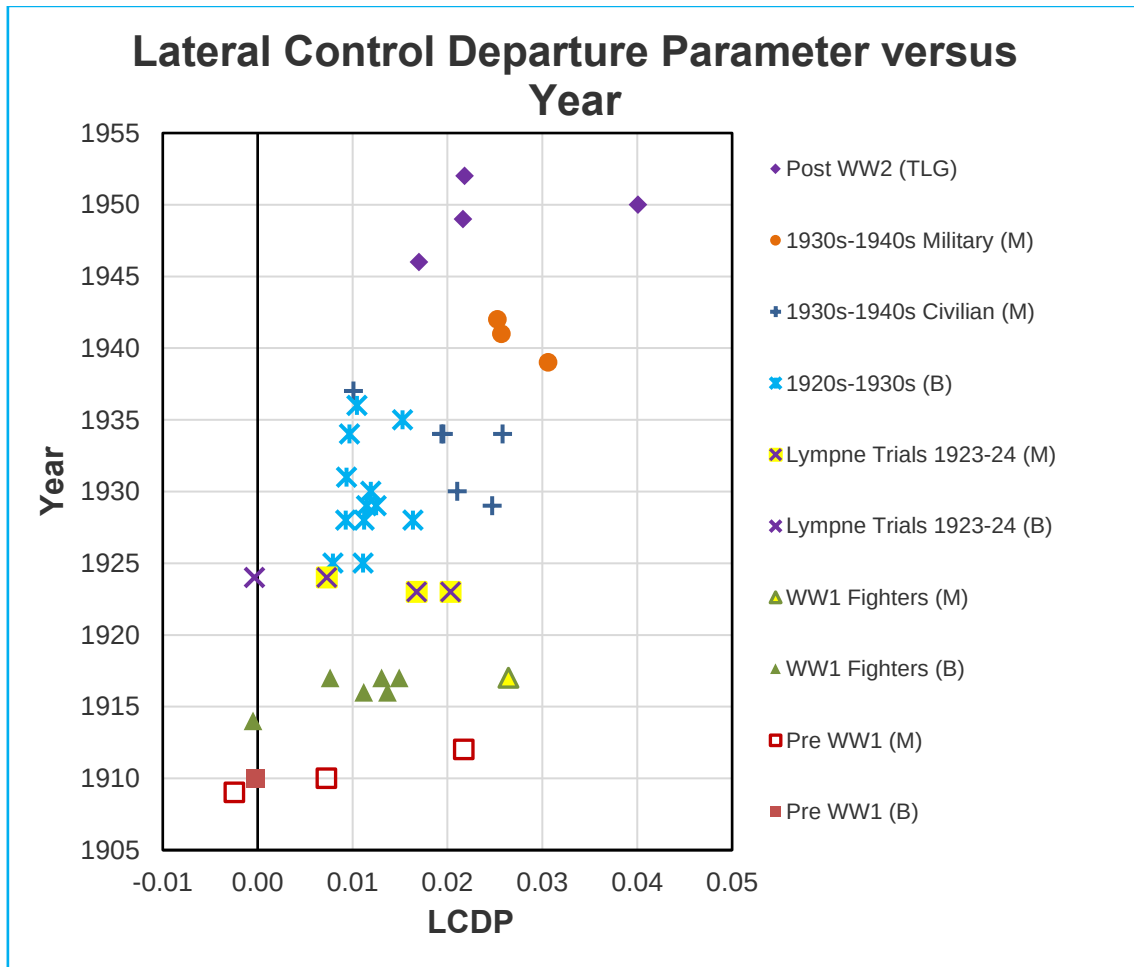


Figure 3-42 - Lateral Control Departure Parameter vs Year

3.6 Summary

The analysis of the longitudinal, directional and lateral stability and control parameters discussed in this section shows the key design changes over time such as horizontal and vertical tail volumes which from a minimum in the WW1 era they have increased steadily reflecting the growing acceptance of the need for robust static stability, but despite this the design of the vertical tails of the biplanes in the 1920s and 1930s required the pilot to provide directional stability. Aileron volume coefficient, when speed range is considered, also shows a steady increase over time.

Many of these early aircraft possess characteristics which have the potential to compromise a modern pilot's attempts to control the aircraft. In the longitudinal axis some are longitudinally unstable, some exhibit neutral or very marginal static

stability, few have the level of longitudinal static stability required of modern certificated aircraft. Some aircraft are close to having negative manoeuvre stability – which can be structurally hazardous when the airspeed is above the manoeuvring speed (V_A) and at lower speeds can result in the aircraft stalling without any control input from the pilot. As shown in the introduction the recorded fatal accident rate due to stall/spin accidents in the era between WW1 and WW2 was very high and would be totally unacceptable today.

These handling differences can cause other problems such as ‘pilot induced oscillations’ (PIO) unless and until the pilot has adapted to the aircraft. The pilot is likely to find the aircraft ‘overly sensitive’ and often attributes this to the control gearing when actually the aircraft has little if any static stability. The pilot may continue to attempt to use the trimming device to establish hands-off pitch trim without appreciating that this is futile if the aircraft does not possess longitudinal static stability.

In the directional axis the in-flight characteristics were compromised for many years by the conservatism of British designers and test pilots – designers who were, for structural considerations, loathe to abandon the biplane in favour of the monoplane and equally loathe to increase weight and complication by adding such things as flaps and wheel brakes. Their test pilots, who probably learned to fly during WW1, valued agility and low control forces and, as mitigation to the unreliable engines of their youth, a low landing speed and a top wing cabane structure over their head to minimise the hazards during forced landing on bad ground. Thus, the industry persisted with flapless, brakeless biplanes capable of landing at 50 mph or less well into the late 1930s. Without flaps or wheel brakes the pilots valued the ability to generate high drag for their landing approach by using large angles of sideslip and when taxiing on the surface they valued the ability to avoid weathercocking into the wind and thus to be able to steer using the rudder without ground crew assistance - wing walkers. Both the sideslipping requirement and the ground steering requirement resulted in aircraft with low levels of controls-free directional stability and overly high levels of directional control. Because the rudders were large, typically horn balances were used to

reduce the control force required to sideslip. Such characteristics compromise the handling qualities in 'normal' flight and pose a serious hazard to the structure as airspeeds increased in the late 1930s. The modern pilot may experience difficulty coping with such an aircraft which will not fly straight without sideslip unless the rudder is constantly restrained, or worse still, needs to be continually controlled as in the Sopwith Camel. Furthermore, the pilot may not appreciate just how powerful the rudder control can be. Inappropriate control gearing may exacerbate this in which very small movements of the rudder pedal generate large rudder deflections and consequently large angles of sideslip – and this will feel very different to a modern certificated aircraft.

Similar and often related problems will be found in the lateral axis. Early pilot training techniques varied but most viewed the rudder as the primary 'turn' control while the lateral control system was used only once the yaw (turn) had been initiated. The amount of lateral control needed would vary depending on the dihedral effect of the actual aircraft type. Those with low dihedral effect needing more lateral control to ensure that the aircraft banked enough while those with high dihedral effect needed less. Lateral control power varied over the period but was lowest in the 1925-1935 era when it was about half that of WW1 biplane fighters which had ailerons on all four wings. This may be because UK civil biplanes in the 1920s-1930s were mostly equipped with only one pair of ailerons which in turn may have been driven by the desire to lighten and/or to simplify the design, particularly for those aircraft built with folding wings. Whatever the motivation, the two-aileron biplane in practice has low roll power and this is often accompanied by low controls-free directional stability, a very powerful rudder and moderate levels of dihedral effect. This combination can mean that, at low airspeed, a greater rolling moment can be generated by deflection of the rudder than can be generated by deflection of the ailerons and especially so if they produce significant adverse yaw. This characteristic can result in loss-of-control accidents when modern pilots do not appreciate that in aircraft with these characteristics, the 'rudder wins.'

However, in aircraft with little or no dihedral effect, such as the 1910 Avro IV, a different challenge may present itself. The Avro IV has no fixed vertical stabiliser and has significant 'fin area' forward of the cg in the form of the upright engine and the forward fuselage skinning. This gives very low directional static stability (<0 with rudder free) and, in this absence of any resistance to sideslip, a very effective rudder. Laterally the absence of dihedral effect means little or no 'rolling moment due to sideslip', and lateral control is limited as it is provided by warping the wings. The spiral mode is likely to be unstable with the rudder fixed. Take a scenario in which a modern pilot is flying this aircraft in a banked turn and wishes to recover to straight flight with some urgency. A large roll input will only provide a modest roll rate but will likely generate some adverse yaw which will be 'into-turn'. The pilot anticipating a 'normal' response may instinctively apply out-of-turn rudder in an attempt to augment the poor roll rate through, what his flight instructor called, the further effect of yaw. Due to the lack of dihedral effect, the rudder will not augment the roll, but the very effective rudder will readily generate a very large angle of sideslip. If the pilot persists in this technique the stick and the rudder may end up fully deflected in the same direction and the aircraft will have a large sideslip angle and, due to the drag caused by this, will be decelerating or descending or both. At low height this can result in an uncontrolled sideslipping descent to the ground. (see 2.1.2) It is therefore essential that modern pilots understand that in aircraft which lack dihedral effect the rudder will not improve roll performance and, in aircraft with these characteristics, to use the rudder only to keep sideslip to a minimum.

4 VINTAGE AIRCRAFT HANDLING QUALITIES COMPARED TO CERTIFICATION SPECIFICATION CS-23.

The fourth objective is to examine modern certification specifications and identify those aspects with which vintage aircraft do not comply and the relevance to their safe operation. (Certification Specifications CS-23 Amendment 4, 2015)

4.1 Performance

4.1.1 Background

This study is concerned primarily with the handling qualities of the aircraft but in the interest of completeness six aspects of aircraft performance are discussed briefly. In terms of aircraft specification, design and certification, performance is concerned with aspects such as take-off run/distance, rate/angle of climb, climb ceiling, maximum level speed, and stalling speed – all except stalling speed being a function of excess power or excess thrust. The other areas of aircraft performance are glide angle, and landing distance/run which are functions of drag. Sufficient performance is when the amount of space (or time) required to complete a manoeuvre (e.g., the distance needed to take-off and achieve a height of 50 ft) is less than the amount of space or time available (e.g., the available length of the airfield before the first obstacle is reached). Although having superior levels of performance is desirable in completing successfully a given mission it falls outside the definition of ‘handling qualities.’ That is not to say that some aspects of power-related effects such as propeller torque, precession, asymmetric blade effect and slipstream may degrade or otherwise complicate stability and control issues in some flight phases.

4.1.2 Take-off run/distance

In current certification specifications the distances required for various take-off evolutions must be measured and scheduled so that a take-off need never be attempted without knowing the available airfield dimensions are adequate. For the period addressed in this study accurate take-off performance data was not

available. In the days of the biplane, with their associated low wing loadings, take-off distances were small and were rarely measured or stated in documentation. As monoplanes appeared, with their higher wing-loadings and associated longer take-off distances, some of the existing airfields became inadequate. Their 1930's manufactures began measuring the take-off distance required and quoting it in relevant documentation.

4.1.3 Climb

Adequate climb performance is essential to safe operations. In current certification specifications the climb gradient achievable after take-off must be measured and scheduled in the flight manual so that it can be determined whether any obstacles along the climb-out path can be cleared, this requirement must also be met with one engine inoperative for multi-engine aircraft. Thereafter, in the en-route phase of the flight the available rate of climb, all engines operating and one-engine inoperative, and the service ceiling are used to demonstrate whether or not any high terrain along the route can be cleared by an adequate margin.

Specific excess power is the parameter which determines rate of climb. Before WW1 the gasoline engine was in its early development and the engines light enough to fit to aircraft were of very low horsepower, typically 25-50 BHP. This left very little excess horsepower for climbing and rates of climb in this era were marginal. With WW1 came the need to climb more quickly than the enemy aircraft and, in this era simple measurements of time to climb were made and reported (although not published at the time as they were top secret). In 1923-24 a series of light aircraft trials were held at Lympne aerodrome with the aim of being able to define the minimum cost civil aeroplane for recreational use. The minimum cost requirement drove the engine size down from the 100-200 BHP common during WW1 back to the 30 BHP level of the pioneering days. Many aspects of performance were examined during these trials, but the conclusion was that a 30-35 BHP engine does not provide sufficient excess horsepower for safe day-to-day operation in the UK environment.

Except for the odd record attempt or dedicated research aircraft, for the next 10-15 years climb performance was not a high priority and a civilian light aircraft capable of climbing at better than about 400 ft/min would have been seen as acceptable, and 800 ft/min would have been seen as exceptionally good. With the approach of WW2 rapid rates of climb and a high combat ceiling once again became priorities for military aircraft and more accurate tests were conducted and reported upon for such aircraft. Even so actual climb performance numbers were secret and not published in aircraft documents such as Pilot's Notes. Since rate of climb is a function of aircraft weight and power it is possible to examine the ratio of weight to horsepower – i.e., power loading to gain an insight into likely levels of climb performance. Power loadings of the subject aircraft are shown.

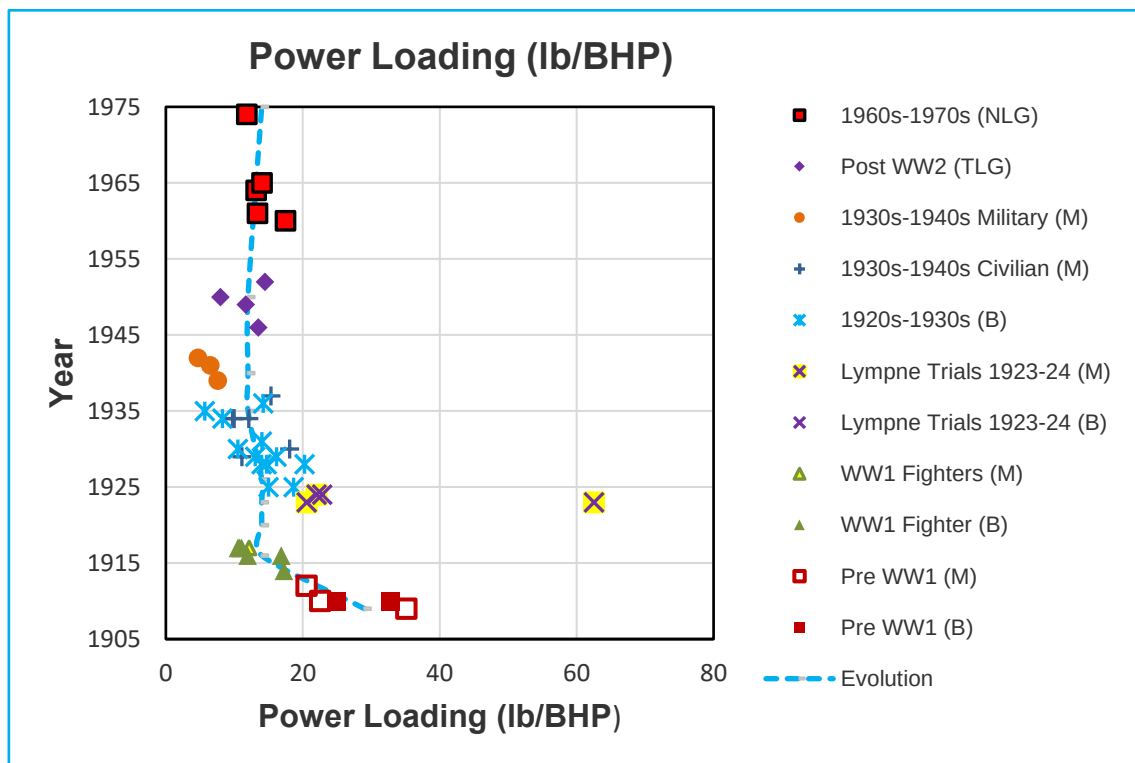


Figure 4-1 - Evolution of Power Loading

Figure 4-1 shows that the Pre WW1 aircraft had very high power loading but from the WW1 Fighters to the present day the power loading lies in the 12-14 lb per horsepower range. There are two groups of aircraft which are clear outliers, firstly the aircraft designed for the 1923-24 light aircraft trials which were limited by the competition rules to utilising engines of very low power, and the 1930s-1940s

military monoplanes which have very high-power engines in relatively small airframes.

4.1.4 Maximum level speed and speed range

Maximum level flight speed occurs when the thrust available from the propulsion system equals the drag of the aircraft. Speed range is the difference between the 1g stalling speed (V_{S1g}) and the maximum level flight speed (V_H). The V_{S1g} is lift related while the V_H is power/thrust related. The greater the speed range the more tractable an aircraft is – the smaller the speed range is the more prone the aircraft is to upset by atmospheric instability and the more likely it is for the pilot to allow the aircraft to stall inadvertently. In the Pre WW1 era, the low engine powers available coupled with the relatively high drag resulted in low values of V_H , which was rarely more than ten knots greater than V_{S1g} . This very small speed range presents a challenge for the pilot especially when flying in less-than-ideal weather conditions as atmospheric disturbance can reduce the margin and put the aircraft in a near-stall condition with associated deteriorating handling qualities or indeed into a full stall condition which could be irrecoverable due to the stability and control characteristics of the aircraft concerned. Accidents of this sort were commonplace before WW1. During WW1 the drive to fly ever faster provided greater speed ranges which gave the aircraft low landing speeds but at the same time the ability to chase down targets and escape from unwinnable combats. In the 1923-24 light aircraft trials the limited engine power available resulted in modest speed ranges and low maximum speeds. While, for more conventional civil aircraft of the interwar period, maximum level speed was essentially a marketing tool, so speed ranges improved as additional horsepower became available. Air races of various sorts were very popular, the Kings Cup being the obvious British example, in which aircraft constructors and pilots tried to show that their aircraft was faster than all the others. Racer designs of the period and military aircraft needed high maximum speeds to be effective in the role although this often resulted in higher values of V_{S1g} . For normal civilian aircraft, once the transition from biplane to monoplane occurred the speed ranges slowly increased over time.

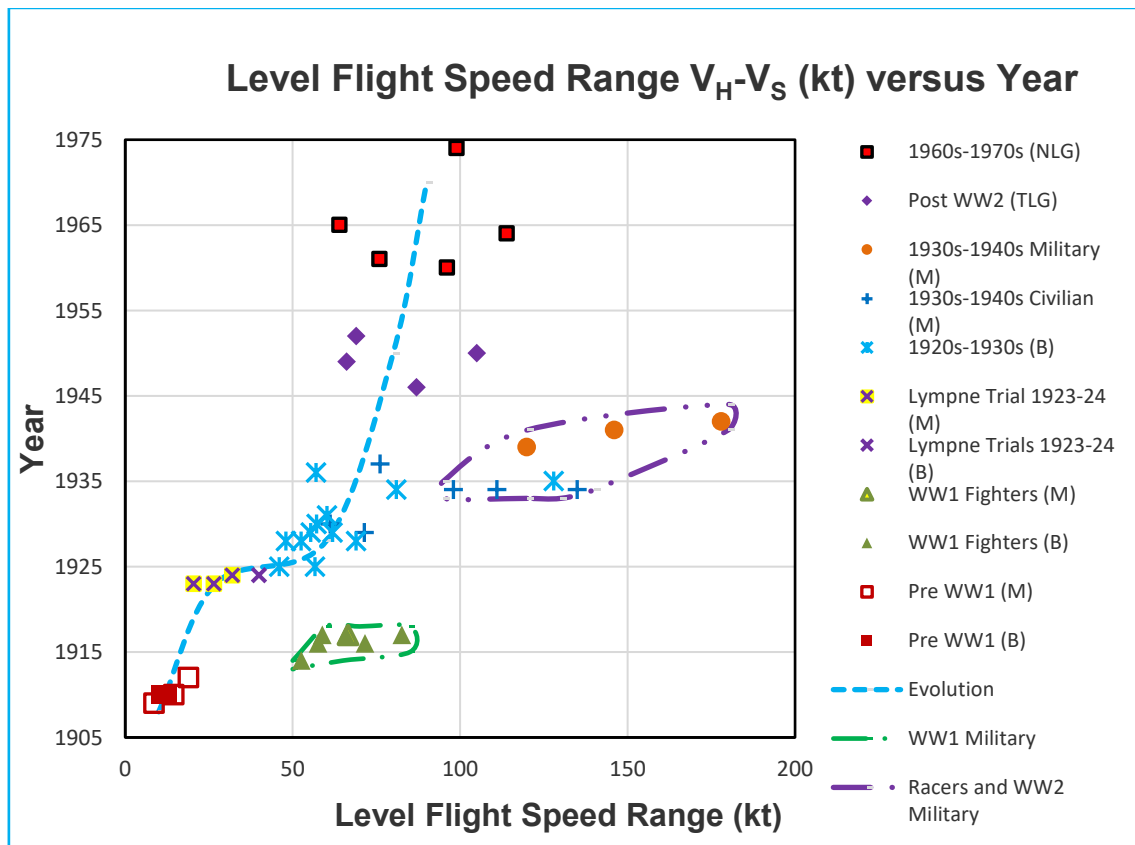


Figure 4-2 - Evolution of Speed Range

Figure 4-2 shows the evolution of speed range. For civilian aircraft it starts at the very low ranges in the Pre WW1 group, it doubles by 1925 and doubles again by 1945. The speed ranges of WW1 fighters highlighted by the green boundary are clearly greater than the civilian aircraft that preceded and followed them. Similarly, the specialist racing aircraft and the WW2 military types show the highest values of V_H but their V_{S1g} must still permit landing in a reasonable distance, so they have considerably larger speed ranges than the norm, therefore they congregate on the high side of the normal evolution highlighted by the purple envelope on the chart.

4.1.5 Stalling speed

In the modern performance context, the stalling speed is the indicated airspeed at which the wing achieves its maximum lift coefficient at the critical angle of attack in 1g flight with idle power/thrust. The value varies with weight and configuration. It is established so that performance critical airspeeds for certain

flight phases including take-off, climb, approach and landing, can be scheduled in the aircraft flight manual, and used to calculate the horizontal space the aircraft needs to complete a given manoeuvre. Therefore, stalling speed is strictly for matters of performance; while the stalling behaviour is a subset of handling qualities and will be addressed below. For the aircraft of this study, original design and operating documentation is usually sparse and often entirely absent. Happily, for such aircraft, it is usually easy to measure the stalling speed by using standard flight test risk mitigation measures.

4.1.6 Glide angle

Determination of glide angle is necessary for single engine aircraft since if the engine fails the aircraft must use its remaining energy to glide to an aerodrome or forced landing area. The distance it can cover is a function of lift to drag ratio (L/D). Tests are made to determine the L/D, which is the inverse of the glide flight path angle (γ), the shallowest glide angle being achieved when L/D is at a maximum, and for a known L/D (or glide angle (γ)) the distance an aircraft can glide in still air is directly proportional to height. While current gliders and airliners have very high values of L/D, most of the aircraft in this study do not, as many are biplanes which have high levels of drag due to their configuration and construction; while many others have low aspect ratio wings which also compromises L/D. Therefore, few of the aircraft in this study would be capable of gliding very far, about one nautical mile (6080 ft) per 1000 ft of height would be a rough average.

When approaching to a glide landing it is sometimes necessary to steepen the glidepath. Typically, biplane pilots would deliberately induce a sideslip condition to increase the drag thereby lowering the L/D to steepen the angle of glide. None of the biplanes in this study group are equipped with landing flaps except the 1935 Gloster Gladiator. Sideslipping a monoplane is not as effective in controlling the glide path angle so, from around 1930, most monoplanes are equipped with landing flaps, or airbrakes of some sort, to steepen their otherwise flat glide angles when on the approach to land. The ability to utilise large sideslip angles

to adjust the approach glide angle was and still is an essential skill when flying an aircraft without flaps or airbrakes.

4.1.7 Landing distance/run

In current certification specifications the distance required to approach over a 50 ft obstacle, land and stop (landing distance required) and the distance from touchdown to stop (landing run) must be measured and scheduled so that a landing need never be attempted without knowing that the available airfield dimensions are adequate. For the period addressed in this study accurate landing performance data was not available. In the days of the biplane their low wing loading and associated low stalling speeds meant that both landing distances and landing runs were small so were rarely measured or stated in documentation. As monoplanes appeared their lower drag, higher wing loading and associated higher stalling speeds meant greater landing distances and it became apparent that some of the existing airfields might be inadequate. So, by the 1930s manufactures began measuring the landing distance required and quoting it in relevant documentation.

A comment on wing-loading. Most of the foregoing parameters are functions of or in some way affected by the aircraft's wing loading, which is the weight of the aircraft divided by the reference wing area.

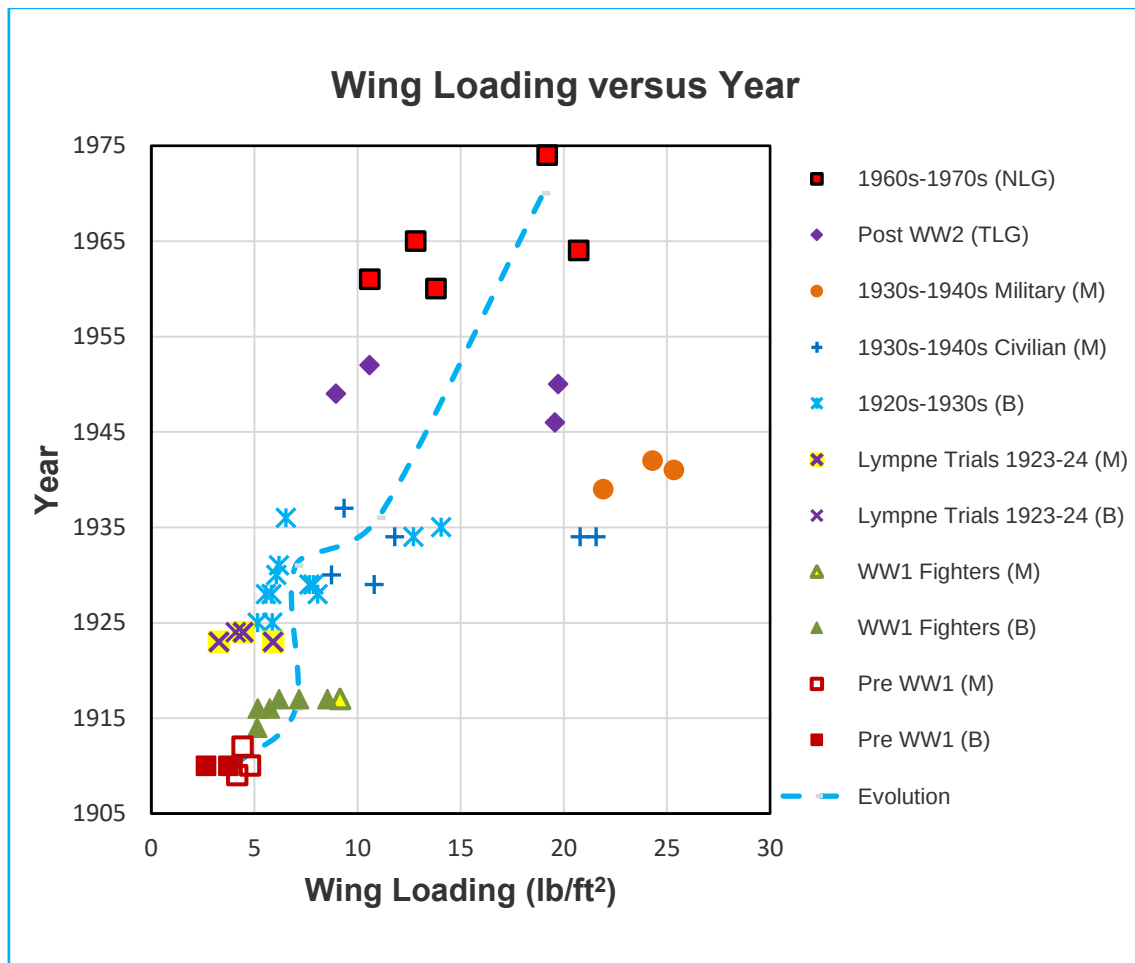


Figure 4-3 - Wing Loading versus Year

Figure 4-3 shows that for the aircraft in this study the wing-loading of the very early monoplanes and most of the 1920-1930s biplanes lie in the range 3 to 9 lb/ft². The wing-loadings of the 1930's monoplanes range from 9 to 25 lb/ft². The 1960-70's light aircraft with nose landing gear have wing-loadings in the range 13-21 lb/ft². A comparison between these relatively modern aircraft and a typical light recreational biplane from the 1930's with a wing-loading of around 6 lb/ft² say, is of interest because the lightly wing-loaded biplane will be much more affected by a given wind gust than a modern aircraft and this can have a detrimental effect on the handling qualities of an aircraft which may be deficient in aspects of stability and control.

4.2 Flight characteristics

4.2.1 Controllability and manoeuvrability

4.2.1.1 General

Recent certification specifications such as CS 23.143 have a requirement that an aeroplane must be safely controllable and manoeuvrable during all flight phases and that it must be possible to make smooth transitions from one flight condition to another including turns and sideslips. This generic requirement is intended to ensure that a pilot will not lose the ability to maintain safe flight when changing flight condition. All aircraft designed after WW2 have little difficulty in complying with this requirement but for earlier aircraft designed before such a requirement was enacted may well have places in their flight envelope where continued control is compromised. A pilot trained only on modern aircraft will need to apply considerable 'pilot compensation'¹¹ to avoid an undesirable event.

4.2.1.2 Control forces

Maximum control forces are now specified depending on the axis, the inceptor type, whether one handed or two-handed, and whether the application of the force is temporary or prolonged. There were no requirements in the past and the control forces in earlier aircraft may be greater than the modern requirement perhaps because of the lack of trim system – it is even more likely that the control forces will be much smaller in earlier generations of aircraft where static stability was low or absent, or due to the design of the aerodynamic balance of the control surface.

The Sopwith Camel requires a continuous push force in the climb and cruise. This push force was measured in (RAE No B.A.251, 1918) as 15 lbf with 'engine on' at 1200 RPM at an altitude of 5000 ft. A pilot accustomed to aircraft that are compliant with this requirement may find holding the required pitch attitudes with prolonged out of trim control forces a significant distraction

¹¹ The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics. (Cooper & Harper, 1969)

4.2.1.3 Longitudinal control

The CS 23.145 requires that the maximum control forces specified must not be exceeded during certain changes of, configuration, airspeed and power setting. This is a requirement to ensure that there is always sufficient nose-down longitudinal control margin to prevent an undesirable condition as configurations change. Earlier aircraft will not necessarily demonstrate these desired characteristics in one or more area. As an example, if full power is applied to make a go-around in the Westland Lysander when trimmed for landing the aircraft will pitch up even with full nose down elevator applied. This characteristic was responsible for a number of fatal accidents during this aircraft's introduction to service.

4.2.1.4 Directional and lateral control

CS 23.147 requires that in a multi-engine aircraft it must be possible to regain full control without exceeding 45° bank, reaching a dangerous attitude or encountering dangerous characteristics in the event of a sudden failure of the critical engine in a given flight condition. Although the multi engine aircraft in this study are compliant with this requirement many of their contemporaries were not. This specification also requires that *'it must be shown that the aeroplane is safely controllable without the use of the primary lateral control system in any configuration and any speed or altitude within the approved operating envelope. It must also be shown that the aeroplane's flight characteristics are not impaired below a level needed to permit continued safe flight and the ability to maintain attitudes suitable for a controlled landing without exceeding the operational and structural limitations of the aeroplane.'* This requirement relies on the rudder being capable of being used to roll and bank the aeroplane and recover to straight flight after the failure of the lateral control system. Most of the aircraft in this study have powerful rudder control and sufficient rolling moment due to sideslip to be compliant but several early aircraft have no dihedral and in those cases the bank angle cannot be controlled with the rudder in the event of a lateral control failure. Pilots trained on aircraft certificated to a post WW2 airworthiness requirement

may not appreciate the significance of flying an aircraft which is not compliant with this requirement.

4.2.1.5 Minimum control speed

Minimum control speed (V_{MC}) is the airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the aeroplane and thereafter maintain straight flight at the same speed with an angle of bank not more than 5° and CS 23.147 requires that V_{MC} must not exceed $1.2 V_{S1}$. Of the multi-engine aircraft of this study, the DH-88 is only just compliant, and the Anson is not. Many of their WW2 military contemporaries are reputed to be unable to comply with this requirement. Such aircraft need a different approach to one engine inoperative flying which may not be obvious to pilots trained on multi-engine aircraft certificated under post WW2 certification rules.

4.2.1.6 Control during landings

CS 23.153 requires that it must be possible safely to complete a landing without exceeding the maximum one-hand control force following an approach to land at 5 knots below the correct speed, with the aircraft in trim, from a steep approach, with only minor power changes. Many early aircraft do not have a pitch trim system so the force to land the aircraft depends on which speed and configuration the aircraft is 'in trim'. The Bristol M1c of this study has no pitch trim and a significant pull force is required throughout the approach and landing.

4.2.1.7 Elevator control forces in manoeuvres

CS 23.155(b)(2) requires that the elevator control force needed to achieve the positive limit load factor may not be less than $W/140$ lbf (where W is in lb) or 15 lbf, whichever is greater. For the 1500 lb Sopwith Camel of this study the minimum pull force would be 10.7 lbf. As reported by the Royal Aircraft Establishment (RAE No B.A.251, 1918) a push force of 14-15 lbf was required to hold 1 g flight and prevent the load factor increasing at airspeeds between 100 and 60 mph with engine on or off, so this aircraft is significantly non-compliant. For the 6800 lb Hawker Hurricane the measured the stick force per g was 4.6 lbf/g, assuming a typical limit load factor of 6g, the stick force at 6g would be 27.6

lbf which is very significantly under the requirement of 48.6 lbf. Such very low stick forces may result in inadvertent accelerated stall when flying below the manoeuvring speed (V_A) or structural overstress when manoeuvring above this speed. In addition, pilot induced oscillations (PIO) are likely until the pilot has fully adapted to the aircraft and a PIO may result in loss of control or structural damage.

Note. Although this requirement is expressed in the CS under 'Controllability' it is a measure of manoeuvre stability rather than controllability.

4.2.1.8 Rate of roll

Rate of roll is a function of lateral control power usually provided by the ailerons or wing warping in the pre-WW1 era. The rudder can also be used to roll the aircraft through $\mathcal{L}_\beta$ – rolling moment due to sideslip - although this is rarely crisp enough for tight control of the bank angle as needed during landing or formation flying. CS 23.157 requires minimum rates of roll in the take-off and approach configurations. For light aircraft these are 12°/sec and 15°/sec respectively. While these are very modest rates of roll which are within the capabilities of many aircraft in this study it should be realised that certain early designs limit the roll rate achievable with the lateral control system due to the wing distorting in the twisting sense thereby reducing the effectiveness of the lateral control. Also, since the lateral control surfaces normally lie outside the propeller slipstream their effectiveness is a function of the airspeed which is at its lowest during take-off and landing. The 1917 SE5a and many of its contemporary WW1 fighters have very little lateral control power at landing speed and for this reason they must be landed into wind as it may not be possible to counter the rolling moments associated with crosswind components during the landing flare, hold-off and rollout – particularly if the aircraft has a high level of dihedral effect.

4.2.2 Trim

The term 'trim' has a number of applications. It can be said that an aircraft is in trim when its flight controls are fixed in a position to bring the sum of the moments to zero. This can be thought of as the engineer's definition of an aircraft being

trimmed in a state of static equilibrium. However, that definition does not address what forces need to be applied to the cockpit controls to achieve that trim condition. If the pilot is holding residual force(s) to achieve the state of 'trim' it is conditional on the pilot maintaining those forces. If the aircraft is equipped with trimming devices the pilot may employ these to reduce the residual control forces to zero so that, if released, the control inceptor stays in the trimmed position and the aircraft remains flying 'in trim'. This can be thought of as the pilot's definition of an aircraft being 'trimmed out' or 'in trim'.

Trimming devices were not commonplace until after WW1 so up to their introduction pilots accepted the need for continuous and varying control forces in one or more axes as a matter of course and such a characteristic requires moderate pilot compensation at best and can lead to loss of control if pilot attention lapses. From the earliest days the incidence of the tailplane was usually adjustable on the ground but during WW1 tailplanes adjustable in-flight using a control in pilot's cockpit were introduced in a few aircraft. As was illustrated in chapter 4, initially these were seen as a device to manage changes in longitudinal load distribution rather than a trimming device to be used continuously during the flight. Contemporaneously German military aircraft were sometimes equipped with a 'brake lever' or damper device which when applied held the stick in a certain place to relieve the pilot of any residual force. After WW1 a common 'trim' system adopted by de Havilland and others was a spring bias applied to the control column similar in concept to the German stick brake. Sometimes control surfaces were 'trimmed' with a small bendable plate or tab; to help achieve trim at a particular airspeed but such tabs are not adjustable in flight. In the late 1920s tabs were made to be adjustable from the pilot's station enabling a range of airspeeds to be trimmed and these are still in use today in most aircraft with reversible flight control systems. Modern light aircraft all have a trim system for the longitudinal axis, occasionally on the directional axis in the form of a rudder trim tab, aileron trim is rarely provided.

The current CS 23.161 requires that it must be possible in all conditions of loading, configuration, speed and power to ensure that the pilot will not be unduly

fatigued or distracted by the need to apply residual control forces exceeding those for prolonged operation. The aircraft must be in lateral and directional trim at $0.9 V_H$ meaning that to hold the aircraft straight and maintain wings level the residual force after trimming should not exceed 10 lbf in pitch, 5 lbf in roll and 20 lbf in yaw. In the aircraft in this study only the twins, the Spitfire and the Provost are equipped with rudder trim tabs and no aircraft in the study are equipped with aileron trim. Many of the biplanes have generous rudder volume, most with rudder horn balance, and in the absence of adjustable rudder trim there is no means to maintain directional trim. This means that such aircraft cannot comply with this requirement and furthermore without continuous pilot restraint of the rudder bar the rudder could deviate from trim or even 'overbalance' to full deflection which may result in an unsustainable flight condition. The same condition could arise if the linkage between the rudder bar and the rudder surface fails.

CS-23.161 also requires that the aircraft must maintain longitudinal trim [and be trimmable] in a climb with high power at the appropriate scheduled climb airspeed, in level flight at any airspeed between V_H and $1.4 V_{S1}$, in a descent at the maximum operating speed, and on a 3° approach at $1.4 V_{S1}$ flaps up and at V_{REF} with flaps set to the landing setting. Few if any of those requirements can be met if the aircraft does not have a longitudinal trim system and many of the aircraft in the study do not. That means that the 'organic envelope protection' normally provided by a statically stable aircraft which can be trimmed to maintain a desired airspeed [or angle of attack] may be lost when flying a 'vintage aircraft' which lacks either stability or trimmability or both, requiring moderate pilot compensation.

4.2.3 Stability

CS 23.171 to 177 specify the level of static longitudinal, directional and lateral stability required for certification.

4.2.3.1 Static longitudinal stability

CS 23.173 requires the following behaviour in climb, cruise and landing flight conditions.

CS 23.173 (a) A pull [force] must be required to obtain and maintain speeds below the specified trim speed and a push [force] required to obtain and maintain speeds above the specified trim speed. This must be shown at any speed that can be obtained [within the operational speed envelope].

This requirement is achievable only when the aircraft is longitudinally stable controls free. If an aircraft is longitudinally unstable the reverse of the requirement is true. i.e. it needs push force to maintain speeds below trim speed* and a pull force to maintain speeds above trim speed.

* If an aircraft is longitudinally unstable the pilot will find it impossible to ‘trim’ it to maintain a steady flight condition hands-free so the concept of ‘trim speed’ is a misnomer. It is more correct to think in terms of a ‘datum speed’ from which any subsequent airspeed changes are measured.

Many of the aircraft in this study are not longitudinally stable, controls fixed or controls free, some neutrally stable while a few are significantly unstable. Such aircraft are non-compliant and require considerable pilot compensation to achieve an equivalent level of safety.

One can see evidence of the assumption that this longitudinal static stability characteristic exists by the method used to teach pilots to maintain a constant altitude (level flight) at different airspeeds. Constant altitude implies a constant flight path angle of zero, to maintain this flight path at different airspeeds requires adjustment of the lift coefficient to ensure the lift remains equal to the weight. Lift coefficient is directly proportional to angle of attack and, if the flight path angle is held at zero, angle of attack change is directly proportional to the pitch attitude change. Assuming zero wing incidence for simplicity, this results in a fundamental equation which every pilot needs to understand.

$$\theta = \gamma + \alpha \quad \text{or} \quad \gamma = \theta - \alpha \quad \text{or} \quad \alpha = \theta - \gamma \quad (4-1)$$

Where θ is pitch attitude, γ is flight path angle and α is angle of attack (assuming wing incidence (i) is zero) – illustrated in Figure 4-4.

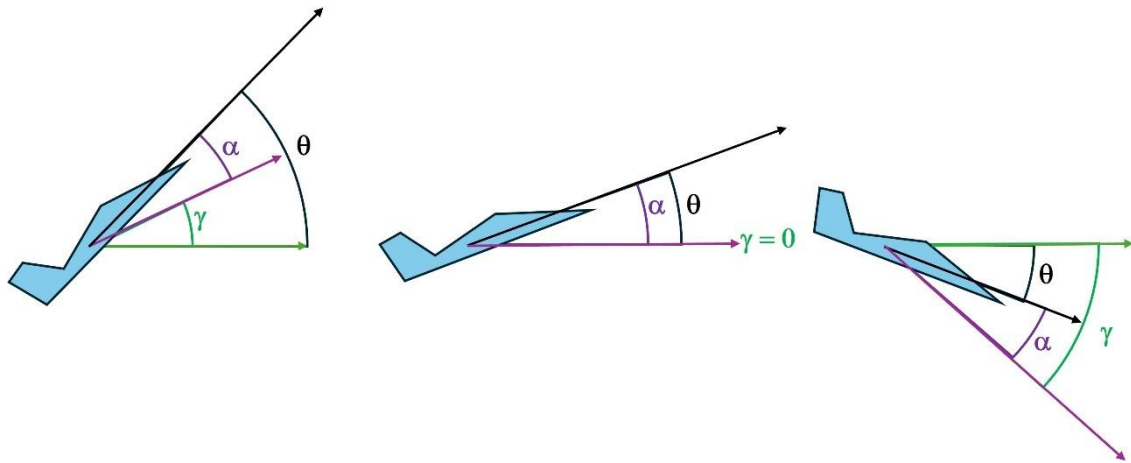


Figure 4-4 – Relationship between Angle of attack (α), pitch attitude (θ) and flight path angle (γ)

The pilot can determine when the flight path angle equals zero by reference to a sensitive altimeter and once stable there, can deduce angle of attack from the pitch attitude as judged by reference to the visual (or instrument) horizon. When changing airspeed in level flight pilots are taught to 'progressively adjust the attitude and trim' [i.e., trim out the pitch stick force] until the airspeed stops changing. During this process both the angle of attack and the airspeed are moving away from the initial condition and the longitudinal static stability will oppose this and generate a restorative pitching moment which must be resisted by the pilot. To maintain each new attitude the pilot must apply a stick deflection and force to negate that pitching moment and then use the trimming device to remove the stick force. The technique described is reliant on the aircraft having controls-free longitudinal static stability. So, here is an example of the pilot training syllabus 'relying' on the aircraft being compliant with the certification specification. The corollary is that when confronted with an aircraft which is unstable requiring non-standard control deflections and/or forces, considerable pilot compensation may be required to maintain an equivalent level of safety.

CS 23.173 (b) *The airspeed must return to within [10% of the trim speed] when the control force is slowly released at any speed within the operational speed range.*

This requirement is designed to limit the amount of control circuit friction to ensure that any demonstration of stability is not compromised. Control circuit friction is rarely a problem in simple light aircraft but can become a factor if the control runs are complex or are not properly maintained. When friction is contributing most of the force felt by the pilot the normal force-airspeed cue used as feedback by the pilot is compromised and this also requires moderate pilot compensation.

CS 23.173 (c) The stick force must vary with speed so that any substantial speed change results in a stick force clearly perceptible to the pilot.

Like (a) above this requirement is only achievable when the aircraft is longitudinally stable - controls free. Its presence means that the pilot becomes aware of a change of airspeed by stick feel without the need to see that change on the airspeed indicator. This characteristic makes it easier for the pilot to maintain a given flight condition, but more importantly it means that if the slows down it will tend to lower its pitch attitude and flight path angle to maintain the trimmed angle of attack, but if the pilot attempts to maintain the original flight path angle a pull force (proportional to the speed change and the static margin) will be required – and this alerts the pilot that things are changing. If there is no noticeable stick force change accompanying speed change it is easy for the pilot to attempt to maintain a desired flight path while allowing the airspeed to decrease and angle of attack to increase (or vice versa) by a potentially dangerous amount unless the airspeed indicator is monitored constantly. Many of the aircraft in this study, and there are examples in all the eras examined from pre-WW1 group to the 1930-1940s group of aircraft, are neutrally longitudinally stable or unstable and may therefore require considerable pilot compensation to maintain safe flight conditions.

NB. In the context of demonstrating longitudinal static stability the certification specification concentrates on airspeed as the criteria which is done so that compliance can be demonstrated without sophisticated flight test instrumentation such as an angle of attack sensor. It is the change of angle of attack that really matters but, in near 1g flight, and assuming constant aircraft weight, the relationship between angle of attack and

airspeed is fixed so that airspeed [change] can be used as a surrogate cue for angle of attack [change].

4.2.3.2 Static directional and lateral stability

CS 23.177 (a) paraphrased states *‘Static directional stability, as shown by the tendency to recover from a wings level sideslip with the rudder free, must be positive for any take off, climb, cruise, approach and landing configurations and this must be shown up to maximum continuous power and at speeds from 1.2 V_{S1} up to the maximum allowable speed Larger angles of side slip up to that at which full rudder is used, at speeds above 1.2 V_{S1} , the rudder pedal force must not reverse.’*

Inter alia, this requirement caters for the failure of the rudder control linkage (rendering the rudder free to float) and a subsequent approach to a landing at 1.2 V_S .

The majority of the aircraft in this study are directionally unstable with the rudder free, partly because their fixed fin volume is deficient and partly because the design of the rudder is such that there is insufficient ‘self-centering’ response when the rudder is unrestrained or free. The situation may be worsened by the destabilising effect of a powerful engine driving a large propeller on the nose of the aircraft through ‘fin effect’. Furthermore, on some aircraft in the study the rudder pedal force reverses at large sideslip angles – so-called ‘over-balance’. This lack of directional static stability requires considerable pilot compensation to achieve and maintain straight, balanced flight which is usually achieved without pilot effort in a typical post WW2 design. There are also implications for continued flight and safe landing following a failure of the rudder control linkage.

CS 23.177 (b) paraphrased states *‘The static lateral stability, as shown by the tendency to raise the low wing in a sideslip, must be positivewith symmetrical power up to 75% of maximum continuous power at speeds between 1.2 V_{S1} and the maximum allowable speed for the configuration being investigated in the take-off, climb, cruise and approach configurations. For the landing configuration the power must be up to that necessary to maintain a three-*

degree angle descent in coordinated flight. The static lateral stability must not be negative at 1.2 V_{S1} The angle of sideslip for these tests must be appropriate to the type of aeroplane but in no case may the constant heading sideslip angle be less than that obtainable with 10° of bank.'

In straight-wing aircraft the rolling moment due to side velocity ($\mathcal{L}_v$), also known as rolling moment due to sideslip angle ($\mathcal{L}_\beta$), makes the largest contribution to lateral stability. Therefore, it is important to recognise that this characteristic provides a rolling moment whenever the aircraft departs from the 'trim' sideslip angle. It does not necessarily provide wing levelling, only the suppression of off-trim sideslip. It arises mainly through 'dihedral effect' which has several contributors, the dominant one being geometric dihedral angle. In the pre-WW1 group, there are two aircraft with dihedral and three without. At that time there were different schools of thought on the subject, some protagonists preferred flat turns made with the rudder in which banking caused by dihedral was seen as an inconvenience, while others preferred banked turns in which dihedral was usually an asset – there was no consensus at this time. Moving into WW1, all the aircraft in the WW1 Fighters group have dihedral to a greater or lesser extent, as do the 1920s-1930s biplanes. One of the characteristics of that period is that many pilots initiated and maintained turns by use of the rudder. From the 1930's, when monoplanes began to replace biplanes there appears to have been a gradual change of emphasis so that the ailerons become the primary control used to roll the aircraft into a banked turn, with the rudder playing a secondary role in suppressing any adverse yaw associated with aileron deflection.

The specification requires that there must be positive lateral stability (i.e., rolling moment due to sideslip) down to 1.2 V_{S1} which is the lowest operational airspeed, ensuring that, in the event of a roll control (aileron) system failure, it will still be possible to adjust and maintain bank angle using the rudder alone and so continue flight to a survivable emergency landing.

CS 23.177 (c) paraphrased states '*In straight study sideslips at 1.2 V_{S1} the aileron and rudder control movements and forces must increase steadily as*

the angle of sideslip is increased up to the maximum.....The larger sideslip angles up to the angle at which full rudder or aileron control is used or the control force limit contained in CS143 is reached, the aileron and rudder control movements and forces must not reverse..... Rapid entry into or recovery from a maximum sideslip must not result in uncontrollable flight characteristics.'

Many of the aircraft in the study group cannot comply with these requirements. Due to small fin to rudder ratio and/or rudder aerodynamic (horn) balance it is common for the rudder force does not increase with increasing sideslip and in some aircraft it reverses. Typically, aileron deflections and forces are compliant while the ailerons were hinged at their leading edges, but when aerodynamic balances are incorporated reversal of aileron forces (over-balance) can occur in some types.

The rotary engines fitted to the WW1 fighters act as powerful gyroscopes when in the upper band of their RPM range, so a rapid yawing entry or exit from a large sideslip angle will cause the aircraft to pitch due to precession, e.g., with a clockwise rotating engine a rapid left yaw will cause an abrupt pitch up. Such a rapid pitch-up, in an aircraft with low or absent longitudinal stability, could take the aircraft to the stalling angle and a spin is likely to result.

Modern pilots expect an aircraft to return to straight flight if the lateral and directional controls are released from a sideslip. That is not so in most of the aircraft in this study in which the lack of self-centering, the low control forces abetted by the seemingly random upsets from the gyroscopic effect of the rotary engine could easily lead to a loss of control. Therefore, considerable pilot compensation is required to maintain a safe flight condition.

4.2.3.3 Dynamic Stability

While the initial response to a disturbance from a trim condition determines the static stability of a system, dynamic stability is concerned with the time history thereafter. Without static stability that subsequent response will be a divergence, if the system is statically stable the response may be a subsidence or an oscillation. In an aircraft the response may be described as having a short period

(typically 2-5 seconds) or having a long period (typically greater than 20 seconds). The amplitude of an oscillation may increase over time (dynamically unstable) or decrease (dynamically stable).

The 'short period pitching oscillation' or SPPO involves changes of angle of attack, normal acceleration and pitch rate and has similar physical characteristics to a Mass-Spring-Damper system. When the angle of attack is suddenly displaced from trim the static stability creates a corrective pitching moment (the Spring), the magnitude of the moment of inertia in pitch (the Mass) affects this response in that the correction usually overshoots the trim condition generating a corrective response in the opposite sense. The oscillation that ensues may continue unless damped and the horizontal tail volume and the pitch rate which together provide the damping action (the Damper).

The combined lateral and directional oscillation or 'Dutch roll' is like the SPPO but in the directional sense where the variables are angle of sideslip, lateral acceleration, and yaw rate. When the angle of sideslip is suddenly displaced from trim, the static directional stability creates a corrective yawing moment, the magnitude of the moment of inertia in yaw affects this response in that the correction usually overshoots the trim condition generating a corrective response in the opposite sense. The ensuing oscillation may continue unless damped and it is the vertical tail volume and the yaw rate which together provide the damping action.

The long period oscillation of the vertical flight path or 'Phugoid' is an oscillation of airspeed and flight path angle while the angle of attack is held substantially constant by the longitudinal static stability. Damping may be positive or negative and is a function of the changes in lift/drag ratio during the oscillation.

CS 23.181(a) paraphrased states *'Any short period oscillation, not including combined lateral direction oscillations, occurring between the stalling speed and the maximum allowable speed must be heavily damped with the primary controls free and in a fixed position.'*

Damping is usually expressed as ratio of the period of the oscillation to the time taken for the all the oscillations to damp out. There is no fixed definition of 'heavily damped' but 'heavily damped' is reported as a damping ratio of 0.30 in (Stinton, 1983) while a value of 0.35 is the minimum acceptable damping ratio for Level 1 handling according to the United States Department of Defense (Military Specification - Flying Qualities of Piloted Airplanes, 1980)

The SPPO is rarely a significant handling qualities concern in the aircraft of this study. Its frequency is a function of manoeuvre margin, tending to zero as the cg approaches the manoeuvre point. Aircraft with low static stability have lower frequency SPPO frequencies. Most of the aircraft in this study have low moments of inertia and so overshoots are minimal. Of the aircraft studied, only the WW2 Hurricane and Spitfire have moments of inertia of sufficient magnitude, (which coupled with low static stability and low pitch damping due to relatively low horizontal tail volume) to contribute to a handling qualities issue. This manifests itself as a form of pitch sensitivity and tendency to pilot induced oscillations which can require considerable pilot compensation.

CS 23.181(b) paraphrased states *'Any combined lateral directional oscillations 'Dutch roll' occurring between the stall speed and the maximum allowable speed must be damped to $\frac{1}{10}$ of the amplitude in 7 cycles, with the primary controls free and in a fixed position.'*

For equivalent reasons the 'Dutch roll' oscillation is not a significant handling qualities concern in the aircraft of this study.

CS 23.181(c) paraphrased states *'Any long period of oscillation of the flight path (phugoid) must not be so unstable as to cause an unacceptable increase in pilot workload or otherwise endanger the aeroplane.'*

Many of the aircraft in this study do not have longitudinal static stability and so exhibit no phugoid oscillation – just a steady divergence. Others, for example the post WW2 Chipmunk, present a divergent phugoid when the cg is towards the aft limit, and are therefore non-compliant with this requirement. In an aircraft which has controls free longitudinal static stability and a phugoid which is adequately

damped the flight path can be controlled by judicious use of engine power/thrust and, if provided and operable, the pitch trim system, such that a safe landing can be made after failure of the elevator linkage. This may not be possible if the aircraft has a divergent phugoid. It is important that pilots of longitudinally stable 'vintage' aircraft discover the phugoid characteristics and how they vary with power and cg position.

4.2.4 Stalling characteristics

Stalling speed was addressed in the earlier Performance section, stalling qualities, i.e., the aircraft behaviour near and in the stall, are discussed here.

4.2.4.1 Wings level stall

CS 23.201(b) paraphrased states that the moment of stalling is identified by either:-

- (1) an uncontrollable downward pitching moment of the aeroplane, or*
- (2) a downward pitching moment of the aeroplane which results from the activation of a device e.g., stick pusher; or*
- (3) the control reaching the stop*

CS 23.201(a) paraphrased states *'It must be possible to produce and to correct roll by unreversed use of the rolling control and produce and to correct yaw by unreversed use of the directional control up to the time the aeroplane stalls.'*

CS 23.201(d) paraphrased states *'During the entry into and the recovery from the manoeuvre it must be possible to prevent more than 15° of roll or yaw by the normal use of controls.'*

These requirements must be met in all configurations and with power idle and with 75% power.

Most of the aircraft in this study comply with 23.201(a) but many do not comply with 23.201(d) because at the stall there is a significant wing drop which cannot be prevented or constrained by use of aileron. In the 1934 DH-88 at the stall the aircraft will typically roll through 60° bank in about 1 second. For the Spitfire the following advice is found in (AP 1565E, 1943):

‘At the stall one wing will usually drop with flaps either up or down and the aircraft may spin if the control column is held back.’

4.2.4.2 Turning flight and accelerated turning stalls

CS 23.203 places additional requirements on the stalling qualities when the stall occurs at 1 kt/sec deceleration rate in a banked turn and with a deceleration rate of 3-5 kt/sec. As above this applies to all configurations and with power off and at 75% power.

CS 23.203 (b) paraphrased states *‘After the aeroplane has stalled it must be possible to regain level flight by normal use of the flight controls but without increasing power and without –*

- (1) Excessive loss of altitude;*
- (2) Undo pitch-up;*
- (3) Uncontrollable tendency to spin;*
- (4) Exceeding a bank angle of 60° in the original direction of turn or 30° in the opposite direction in the case of turning stalls;*
- (5) Exceeding a bank angle of 90° in the original direction of the turn or 60° in the opposite direction in the case of accelerated turning stalls; and*
- (6) Exceeding the maximum permissible speed or allowable limit load factor.’*

Of the aircraft in this study, the 1934 DH-88 is non-compliant with condition (1) and (4) and many aircraft in the study cannot comply with (4) and/or (5) due to their tip stall/wing drop characteristics. For example, for the Spitfire V, (AP 1565E, 1943) state:

‘This aircraft has sensitive elevators and if the control column is brought back too rapidly in a manoeuvre such as a loop or a steep turn, stalling incidence may be reached, and a high-speed stall induced. When this occurs there is a violent shudder and clattering noise throughout the aircraft which tends to flick over laterally, and unless the control column is put forward instantly, a rapid roll and spin will result.’

Improved behaviour during accelerated stalls is evident in the Pilot’s Notes of the post-WW2 Chipmunk primary trainer (AP4308A, 1950) which states in para 34

Stalling. '(v). The stall in a steep turn is indicated by buffeting but there is normally no tendency to flick out of the turn. (vi) Recovery in all cases is straightforward and easy.'

Modern pilots flying vintage aircraft must not assume that the stalling qualities of the aircraft that they fly will be compliant with the current certification standards, many such aircraft have stall behaviour which is potentially dangerous and may require extensive pilot compensation.

4.2.4.3 Stall warning

Stall warning is how the approaching stall is manifested so that the pilot can take preventative measures in time to avoid entering a stalled condition. The term stall warning encompasses the type, effectiveness and timeliness of the warning.

CS 23.207 (a) paraphrased states '*There must be a clear and distinctive stall warning.....*'

CS 23.207 (b) paraphrased states '*Stall warning may be furnished either through the inherent aerodynamic qualities of the aeroplane or by a device that will give clearly distinguishable indications ...*'

CS 23.207 (c) paraphrased states '*...the stall warning must begin at a speed exceeding the stalling speed by a margin of not less than five knots and must continue until the stall occurs.*'

CS 23.207 (d) paraphrased states '*....the stall warning must not occur during a take-off orduring an approach to landing.*'

CS 23.207 (e) paraphrased states '*....the stall warning must begin sufficiently involved in advance of the stall for the stall to be averted by pilot action taken after the stall warning first occurs.*'

The warning provided by 'inherent aerodynamic qualities' of the aeroplane is usually taken to mean light buffeting of the elevator which the pilot can feel through the pitch inceptor – also known as 'natural' stall warning. None of the aircraft in this study are fitted with artificial stall warning and a significant number of them provide no 'natural' stall warning at all while some do but at less than 5

kt before the stall. None of the aircraft exhibit stall warning on take-off but tailwheel aircraft are usually landing in a three-point attitude which is very close to the stalling angle of attack and therefore an aircraft with natural stall warning will be providing stall warning (if it exists on that aircraft) before it has touched down. A few vintage aircraft exhibit 'aileron snatch'¹² at high angle of attack which can initiate a wing drop with no other stall warning. For these reasons a typical vintage aircraft is not compliant with one or more of these stall warning requirements.

Modern pilots flying vintage aircraft should not assume that they will receive adequate stall warning and therefore considerable pilot compensation may be required to avoid unintentional stalls.

4.2.5 Spinning

CS 23.221 addresses the spinning qualities required for normal, utility and aerobatic aircraft. Of the aircraft in this study spinning is prohibited on all except those which are cleared for aerobatic operations namely, Tiger Moth, Blackburn B2, Spitfire, Chipmunk, and Percival Provost. The biplane Tiger Moth and the Blackburn B2 are less prone to enter spins due to being equipped with Handley Page slats on the outer wing leading edges which significantly delay separation and almost eliminate wing drops at the stall. (Handley Page, 1921) Handley Page slats were invented around 1920 and for many years thereafter were mandated on aircraft purchased by the Air Ministry to reduce the unacceptably high number of stall/spin accidents being experienced in the 1920's. The spinning characteristics of the biplane Tiger Moth and Blackburn B2 are quite benign but the Spitfire spin involves a very considerable loss of height and a very real possibility of stalling and re-entering a spin if the recovery from the dive is rushed. The Spitfire Pilot's Notes (AP 1565E, 1943) provides the following cautions:

'The loss of height involved in recovery can be very great and the following height limits are to be observed:

¹² Reversal of aileron hinge moment

- a) *Spins are not to be started below 10,000 feet.*
- b) *Recovery must be started not lower than 5000 feet.*

A speed of over 150 m.p.h. I.A.S. should be attained before starting to ease out of the resultant dive.'

Note: The Spitfire V 1g stalling speed is quoted as 73 m.p.h. IAS (77 m.p.h. EAS); given this, a load factor of 4g is achievable at 150 m.p.h. therefore this warning suggests that the stick deflection and/or stick force per g is so low that a pilot could easily induce a secondary stall inadvertently i.e. with very little deflection of, or very little force applied to, the elevator control. Such a characteristic is indicative of a very low manoeuvre margin.

Spinning was removed from the private pilot's training syllabus some decades ago, so many current pilots will have not practiced how to recognise, or recover from, a spin. Vintage aircraft are more likely to spin when stalled than current designs so modern pilots who fly them may not be adequately prepared or sufficiently skilled to recover from an unexpected spin promptly, unless they have acquired the necessary skills through extracurricular training.

4.3 Ground handling characteristics

4.3.1 Longitudinal stability and control

CS 23.231 (a) states '*A land plane may have no uncontrollable tendency to nose over in any reasonably expected operating condition including rebound during landing or take-off. Wheel brakes must operate smoothly and may not induce any undo tendency to nose over.*'

The requirement is easily satisfied for aircraft with nosewheel landing gear. For aircraft with 'conventional' * i.e. tailwheel landing gear the propensity to nose over is nearly always present subject to the juxtaposition of mainwheel and cg locations, use of wheel brakes (when so equipped), use of power, condition of the surface, and relative wind velocity.

* The expression conventional originates from the time when a tailskid/tail wheel layout was the norm, while tricycle gear was seen as the new thing.

Conventional landing gear comprises of the main gear, carrying most of the weight, set somewhat forward of the aircraft's centre of gravity, with the tail of the aircraft resting on a small tailwheel or tailskid. For non-pilots and pilots who have no experience of tailwheel aircraft the significance of this layout is explained in Appendix E.

Aircraft regarded as 'tail heavy' and are less prone to nose over, examples in this study are the DH-88 Comet and the Westland Lysander. Aircraft regarded as 'tail-light' are at higher risk of a nose over accident, examples in this study are the Spitfire, and Percival Provost.

Pilots of vintage aircraft with 'conventional' landing gear must be aware of this characteristic and the factors which singly or in combination may result in a nose-over. Managing this risk requires moderate pilot compensation compared to that required in a nosewheel aircraft.

4.3.2 Directional stability and control

CS 23.233 (a) states '*A 90° cross component of wind velocity demonstrated to be safe for taxiing take-off and landing must be established and must not be less than 0.2 V_{SO} .*'

The average V_{SO} of the Pre-WW1 group is 31 kt and 0.2 V_{SO} is therefore 6 kt. For the WW1 fighters this rises to 7 kt, the Lympe Trials group is down 6 kt. Few of these aircraft can tolerate such a crosswind component since only a few have steerable tail skids and none of them have differential wheel brakes to assist steering on the ground. In the 1920-1930s biplanes group the value is 8 kt, which is about the maximum that most can tolerate. In this group more have steerable tailskids but only the later military types have differential wheel brakes. For the 1930-1940s civil monoplane group the value is 11 kt, two of the group have no brakes and a non-steerable tail skid and these aircraft are difficult to manoeuvre accurately on the ground, while the remaining four have steerable tailskid/tail wheel and differential wheel brakes. For the 1930s-1940s military monoplane group the value is 13 kt, and for the Post WW2 group it is 10 kt, all these aircraft have steerable tailwheels and differential wheel brakes. Finally, for the 1960-

1970s tricycle aircraft group the value is 12 kt. All these aircraft have the tricycle layout which is directionally stable on the ground and are equipped with steerable nosewheels and wheel brakes and are capable of operating in a significantly greater crosswind component than the minimum requirement.

CS 23.233 (b) states '*The aeroplane must be satisfactorily controllable in power-off landings at normal landing speed without using brakes or engine power to maintain a straight path until the speed has decreased to less than 50% of the speed at touchdown.*'

The ability to comply with this requirement is a function of layout i.e., directional static stability and control, the design of the tail or nose wheel, and any crosswind component. An aircraft with strong directional stability will seek to maintain zero sideslip but when landing with a crosswind the sideslip angle increases as the aircraft slows down increasing the weathercock tendency. If that aircraft has no means of steering on the ground, be that directly or with differential use of the brakes, the aircraft will likely diverge and fail to comply with this requirement – furthermore directional control may be lost to a greater or lesser degree in a ground-loop which can result in aircraft damage. All the vintage aircraft in the study group suffer from this to a greater or lesser extent, the Gladiator and Hurricane require considerable pilot compensation in this regard.

CS 23.233 (c) states '*The aeroplane must have adequate directional control during taxiing.*'

Many of the aircraft in the study group are non-compliant with the regulation because of the lack of adequate steering of the tailwheel/skid and/or the lack of differential wheel brakes.

Aircraft with a tailwheel/skid require considerable pilot compensation when considering the effects of such things as wind angle, ground slope, surface type and condition inter alia. Added to this, the restricted forward field of view in the tail-down attitude also requires additional vigilance to maintain control when manoeuvring on the ground. See 6.2.7.

4.3.3 Operation on unpaved surface

CS 23.235 requires satisfactory characteristics when taxiing on unpaved surfaces. With the exception of the 1960s-1970s group all the aircraft studied were expected to operate from unpaved surfaces. Those with the largest diameter wheels cope the best, and low wheel loading when the going is soft is an obvious advantage. Tail skids are more effective as a braking device when the ground is soft and ineffective on a paved surface. Many early aircraft have a cross axle between the mainwheels which is relatively close to the ground e.g., all the WW1 fighters and the post WW1 DH-60. When operating in long grass or standing crops such axles present a very real nose-over hazard. Later, design changed to a split axle e.g., DH-60X and Desoutter, and eventually to no axle at all e.g., Gloster Gladiator. These later designs are much safer when carrying out an off-airfield forced landing. Incidentally, for the monoplanes with retractable landing gear such as the DH-88 Comet, Hurricane and Spitfire off-airfield forced landings were usually made with the landing gear retracted to avoid a potentially fatal nose-over which could trap the pilot under the overturned aircraft with no means of escape.

4.4 Summary

To summarise the findings discussed above, for each of the aircraft in the study group the number of non-compliances with the current CS-23 has been estimated based on the analysis. The number was then associated with the year of aircraft manufacture to illustrate how the deficiencies evolved over the period of interest.

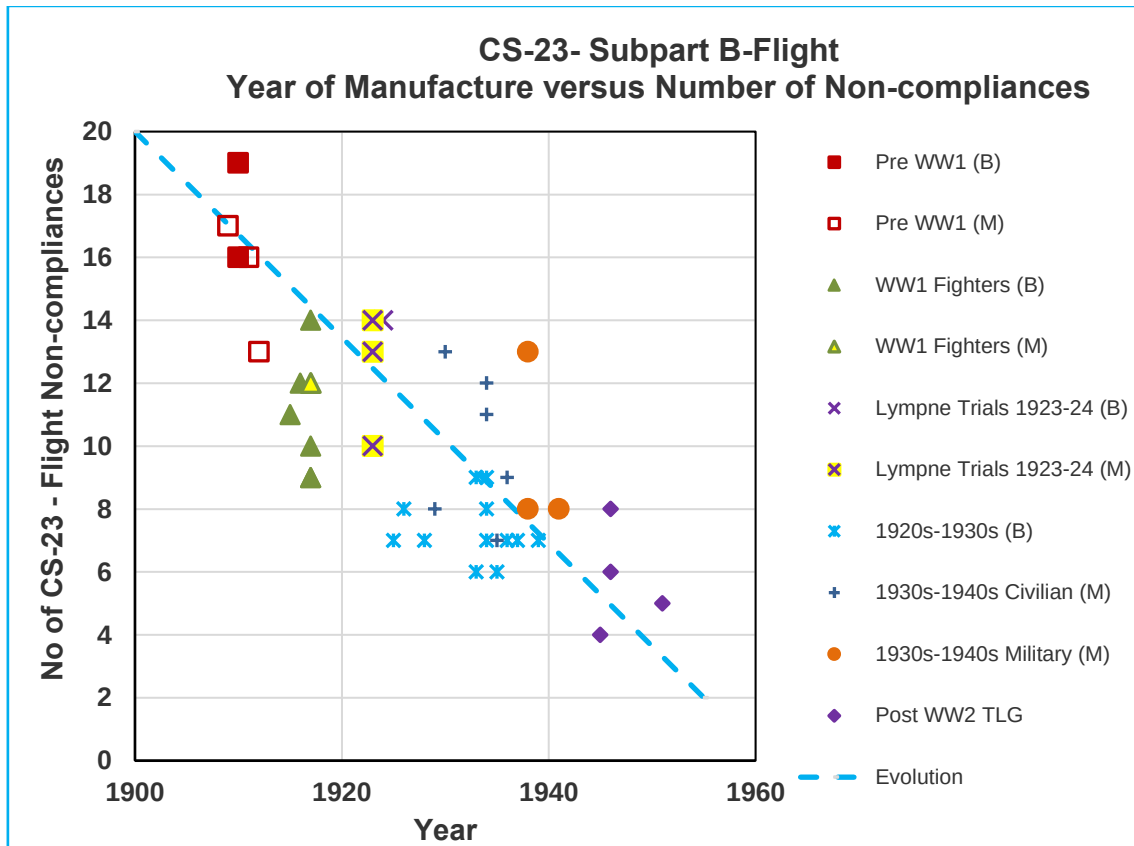


Figure 4-5 – Year vs No of CS-23 Non-Compliances

Figure 4-5 shows how stability and control deficiencies have reduced over the period of interest and is indicative of the additional pilot awareness and workload associated with flying vintage aircraft. Every deficiency in handling qualities requires additional pilot compensation and generally, the older the aircraft the more compensation will be required.

5 OTHER FACTORS AFFECTING HANDLING QUALITIES

'Handling qualities are those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.'(Cooper & Harper, 1969)

'It [handling qualities] includes more than just stability and control characteristics. Other factors that influence the handling qualities are the cockpit interface (e.g., displays, controls), the aircraft environment (e.g., weather conditions, visibility, turbulence) and stress, the effects of which cannot be readily separated'(Cooper & Harper, 1969)

5.1 Cockpit Interface

Many vintage aircraft have open cockpits for the pilot, and some require canopies to be open for take-off and landing to facilitate emergency egress. The pilot is therefore exposed to an environment which can be draughty and noisy and in some aircraft to an extreme degree. This can be a source of major distraction until the pilot has adapted to the environment and this may require moderate pilot compensation to maintain an equivalent level of safety compared to the comfortable, quiet cockpit enjoyed in modern aircraft. The anthropometrics of the human body has changed over time, and it is on average 100mm taller than it was in 1900. Vintage aircraft are not usually equipped with adjustable seats or adjustable rudder pedals which can mean that today's pilot may not 'fit' the cockpit which will impact on his ability to use the control inceptors to the full extent and that may have a bearing on the perceived handling qualities.

5.1.1 Displays

Just like aircraft themselves, cockpit instruments have evolved over the period of study. In the case of the 1912 Blackburn there is only one instrument and that is engine RPM. A means of displaying dynamic pressure to the pilot in terms of airspeed had appeared by WW1, some of these being a typical dial as now, others taking the form of a glass U-tube, or a wing strut mounted spring-loaded plate which moved over a scale as 'q' changed. When first fitted, altimeters were

rudimentary single pointer instruments which read between zero and 20,000 in less than one rotation so 1000 ft gradations appeared every 15-20 degrees or about 1 cm. Such instruments do not have the resolution for accurate height keeping. Early aircraft were often fitted with lateral inclinometers (which is no more than a bubble spirit level) which responded to lateral acceleration – often associated with a sideslip condition. At the time pilots were taught to ‘chase the bubble with the stick top’ to keep the aircraft in balance when turning. The bubble moves in the opposite sense to the slip (or balance) ball seen in current instruments. These were replaced by combined Turn and Slip Indicators in which the slip indicator is an upwards pointing needle reading on a scale, somewhat misleadingly calibrated in degrees, under which is a downwards pointing needle displaying rate of turn. This instrument is inverted when compared to a 1960s Turn and Slip Indicator and very different to the later Turn Coordinator. These differences mean that the interpretation of such instruments is not intuitive to a pilot accustomed to modern flight instruments who may apply rudder in the opposite sense to that required. Early magnetic compasses were inadequately damped and typically spin during, and for a significant time after, turning manoeuvres. Later compasses, while adequately damped, are not intuitive to a modern pilot and some were mounted such that they have to be read via a mirror! When magnetic compasses were augmented by gyroscopic Direction Indicators the limited mechanical technology available resulted in a display which reacts in the opposite direction to that which seems intuitive. In the UK the first gyroscopic artificial horizons (attitude indicators) appear in the late 1930s, but these are typically fitted with a ground pointer which moves in the opposite sense to the more ubiquitous sky pointer. These display characteristics present significant challenges to rapid intuitive interpretation for a pilot accustomed to modern instruments and may require considerable pilot compensation.

5.1.2 Controls

In this context ‘controls’ are those inceptors in the cockpit which the pilot uses when operating the aircraft – they include those for: flight controls, trimming

devices, wheel brakes, high lift devices, engine throttle and mixture, propeller pitch, fuel selectors, and electrical switches.

Human pilots adapt to the inceptor forces needed to accomplish the flying task in a particular aircraft. When those forces are different from those the pilot has adapted a transition period is needed during which the pilot adapts to the new 'feel'. Different aircraft have different force characteristics each requiring pilot adaptation for successful control and perhaps avoidance of PIO. Typically, a pilot is much less aware of control inceptor deflection in the control task, unless of course it reaches a hard limit. However, the ratio of inceptor movement to surface movement – usually referred to as control gearing - can influence handling qualities. For example, the rudder bar of the DH-82a Tiger Moth moves approximately 100 mm fore and aft but that movement commands a rudder angle change of 60 degrees, which is less than 2 mm pedal movement per degree of rudder angle. Therefore, a small linear movement of the rudder pedal can create a significantly large angle of sideslip.

All the aircraft in the study except one use fore and aft movement of a control column for pitch, while roll control is by lateral movement of the stick or rotation of a wheel. The rudder is actuated by the feet via a centrally pivoted bar or parallel action pedals. In the case of the 1912 Blackburn the pitch control inceptor must be moved up and down for pitch control requiring considerable pilot compensation.

Pitch trim controls may be in the form of a lever or a wheel, but their sense of action is always intuitive if mounted to operate in the fore and aft sense. The post-WW2 PA-28 trim is a roof mounted crank operating in the lateral plane. The sense of action of a rudder trim is correct if the axis of rotation is vertical i.e., parallel with the z-axis; in the case of the Spitfire the axis is parallel with the y-axis which is not intuitive there is therefore the potential for mis setting and/or movement in the wrong direction.

Typically, if differential wheel brakes are provided in a vintage aircraft, they are intended assist steering on the ground rather than for significant braking to shorten the landing run, as in tricycle aircraft. Wheel brakes may be actuated by

a variety of inceptors. There may be a hand lever which applies brakes to both wheels, and this may then provide differential braking for steering on the ground when the rudder control is deflected from central. Alternatively, toe operated brake controls may be incorporated with the rudder pedals, or separate heel brake pedals may be installed adjacent to the rudder pedals. Tricycle aircraft are directionally stable on the ground and typically, have a directly steerable nosewheel and toe brakes making ground operations simple and intuitive. Vintage aircraft typically have the 'conventional' (i.e., tail wheel) landing gear layout which is directionally unstable on the ground meaning directional control can be a high-gain closed-loop task requiring rapid reaction to yaw deviations to maintain directional control. If the differential wheel brake system is not intuitive in operation considerable pilot compensation may be required to maintain directional control. In the interwar period a ratcheted handbrake lever to set the amount of braking with the rudder pedal providing asymmetric brake application for directional control became the standard for mechanically operated systems. WW2 British fighters, with pneumatic brakes, are fitted with a short brake lever on the control column grip which can be modulated by the right hand while operating the flying controls at the same time, with differential braking effected when the rudder pedals are deflected. From personal experience this seems the best mechanisation for tail wheel aircraft. Toe brakes were used in Germany and the USA but are better suited to tricycle aircraft. Heel brakes are often provided when the fitting of brakes was an 'afterthought' for that aircraft type, and they offer the least intuitive/most problematic installation.

Engine power is usually controlled through a carburettor with cockpit controls of throttle and mixture. The throttle control normally takes the form of a lever (or plunger) in which forward movement demands increased power which is seen as normal in UK practice and is therefore intuitive. Only the 1909 Bleriot (of French design) uses a mechanisation in which rearwards movement gives more power. Mixture control mechanisation varies. In a typical modern aircraft, the mixture lever gives rich mixture when fully forward and shuts off fuel entirely when the lever is fully aft. In most inter-war and WW2 British aircraft the mixture lever moves in the opposite sense, being full rich when fully aft. Often there is an

interlink between the throttle lever and the mixture lever which prevents the mixture lever moving ahead of the throttle and to ensure that the mixture is moved back to rich whenever the throttle is closed. This mechanisation is non-intuitive for pilots accustomed to modern aircraft. In addition, some early aircraft are also fitted with ignition advance and retard controls in the cockpit usually in the form of a separate lever. The ignition is set retarded for engine start but must be 'advanced' if full power is to be achieved. This complication adds to pilot workload requiring moderate pilot compensation to avoid mishandling of the engine.

Some aircraft in the study group are fitted with variable pitch propellers, all but one of which also incorporate a so-called 'constant speed unit' operated by a fly-weight governor to maintain a selected propeller RPM. The control inceptor is typically in the form of a lever in which maximum RPM (needed whenever full power is required) is with the lever fully forward in similar manner to the throttle. The Lysander is fitted with a two-pitch propeller operated by a plunger type control in which fully forward gives fine pitch – high RPM. These mechanisations are the same in modern aircraft and require minimal pilot compensation.

Fuel selectors are of many different types and provide ample opportunity of mis – selections. To ensure the fuel selector is in the correct position can require moderate pilot compensation – particularly should an urgent requirement to change tanks occur in flight.

In modern aircraft cockpits colour and/or shape coding is used to differentiate between switches and controls of different function. That is not necessarily so in earlier aircraft e.g., the Lysander has six plunger type controls, the one for propeller control is shape coded while the remaining five are identical in appearance and actuation and operate: Carburettor slow-running cut out, Rudder bar adjustment, Cockpit heating, Carburettor heating, Oil cooler bypass. The possibility for mis-selection is obvious and moderate pilot compensation is required to mitigate that hazard.

5.2 Aircraft environment

Typically, vintage aircraft are constrained by the operational regulations to flights in daylight and clear of cloud such that the pilot can fly in visual contact with the ground at all times, meaning that flight by sole reference to flight instruments should never be required. Therefore, for the purpose of this study the following discussion is limited to flights made in 'visual meteorological conditions' (VMC).

In (Cooper & Harper, 1969, p. 3) such factors as: 'weather, turbulence, wind shear, visibility, crosswind, altitude and speed etc.' are listed but when considering low-speed aircraft, wind fraction (i.e. ratio of wind speed to aircraft speed) can be a very significant factor also, particularly when operating at low height.

5.2.1 Weather

In aviation circles the term 'weather' includes such things as: fog, mist, haze, and types and intensity of precipitation; while wind, visibility, cloud amount, air temperature, dew point, and atmospheric pressure are reported separately.

Fog, mist and haze affect visibility, but the legislation sets a minimum visibility for VMC so in the context of this study these are not considered further. Water droplets from dew or drizzle sticking to the wings can reduce the lift/drag ratio and degrade performance in the very slow Pre-WW1 group and precipitation can be a factor in handling qualities in that it may introduce a significant distraction which adds to pilot workload, in addition those aircraft which historically were fitted with gunsights typically have optically flat windscreens which become completely opaque in moderate rain.

5.2.2 Turbulence

Turbulence brings all the effects associated with modern aircraft but in vintage aircraft those effects may be exaggerated if an aircraft is unstable in one or more axes or has poor lateral control power such as the Miles Magister. In addition, for the very low power aircraft from before WW1 (or the Lympne Trials group) the pilot inputs to maintain the desired flight path in turbulent conditions cause

additional drag which compromises climb rate. These factors may require extensive pilot compensation for control in unfavourable conditions.

5.2.3 Wind Effects

Wind can affect vintage aircraft in many ways both on the ground and in the air. Requirements for ground operation were addressed in 4.3.2. The effects of wind on a vintage aircraft in low altitude flight and the effects of crosswind and tailwind components are discussed in 6.2.7.

5.2.4 Motion cues

The pilot often uses motion cues from aircraft responses to assist the control task, but these cues may be masked in unfavourable weather conditions particularly if the aircraft is deficient in stability and/or control in one or more axes, as many vintage aircraft are.

5.2.5 Pilot stress

Pilot stress may arise as result of deficiencies in stability and control and/or any of the other factors described above and the level of stress will be related to how much effort is required to maintain control. Above a certain level pilot stress will reduce performance. It is important to control the level of pilot stress by mitigation measures designed to limit the number and magnitude of the deficiencies to be dealt with at one time.

5.3 Summary

This section highlights the wide range of factors which are not stability and control related but which can degrade the handling qualities of the aircraft by requiring pilot compensation to interpret an unfamiliar display or inappropriate gradations on a dial, to cope with a non-intuitive control movement, or maintain safe flight in weather conditions which might overpower the control authority or the performance of the aircraft. Such factors can accumulate in combinations to the detriment of safe flight and pilots of vintage aircraft should seek to minimise such factors – particularly when they are unfamiliar with the aircraft type.

6 GUIDANCE FOR MODERN PILOTS FLYING VINTAGE AIRCRAFT WITH HANDLING DEFICIENCIES

6.1 Discussion

The fifth objective was to identify aspects of aircraft that may prove challenging to modern pilots to increase their awareness of the possible hazards and suggest mitigation methods.

In chapter 2 interpretation of the contemporaneous pilot reports revealed numerous examples of challenging aircraft, inadequate understanding and flawed training methods which were likely to have causal factors in the numerous accidents that occurred in those days. In chapter 3 the detailed analysis of the longitudinal, directional and lateral stability and control characteristics of the 46 aircraft in the study revealed which aircraft were likely to be unconventional or challenging in one way or another. In chapter 4 the comparison between the current certification specifications and the characteristics of aircraft in the period of study showed that in general, the older the aircraft the more non-compliances or deficiencies can be anticipated. Chapter 5 discussed other factors which can affect handling qualities which can reduce a pilot's spare capacity. Aircraft environment factors were discussed because while in clear, smooth air and when flown gently in the heart of their flight envelopes most of these old aircraft might seem entirely normal, but that is not usually the flight regime where mishaps and accidents occur. It is when the wind is strong or gusty, with associated turbulence, wind shear and/or wind gradient, or when the horizon is indistinct or other external factors arise such as obstacles or a busy traffic environment, or during emergencies that deficient handling qualities can result in mishandling which may then precipitate an accident. Handling qualities deficiencies require pilot compensation and, when coupled with the external distractions listed above, a pilot can become overloaded or overwhelmed by the control task.

6.2 Dealing with deficiencies

To limit the scope of the following discussion it can be assumed that any vintage or replica aircraft which is airworthy, or on the path to airworthiness, will fly under

the auspices of the Civil Aviation Authority (or a delegated organisation such as the Light Aircraft Association). Therefore, the structural integrity, power plant et al will be the subject of a Certificate of Airworthiness or an Airworthiness Approval Note which will set out limitations on mass and balance and airspeed, inter alia. Those aspects of preparation for flight while vital for safety are outside the scope of this discussion.

In this section the findings of the study are utilised to provide some guidance to modern pilots on how to identify and mitigate handling qualities deficiencies. Many of the deficiencies in vintage aircraft can be mitigated on dual control types by having flight instruction or another pilot who has recent experience of the type can provide a briefing; however, these options are not always possible or reliable. The aircraft might be a single seater, or there may be no surviving pilot of the aircraft type concerned to consult with. If there is a type-experienced pilot around he/she may have adapted to the aircraft so effectively that they are no longer an objective judge, or they may have only flown the aircraft in a benign environment and have not discovered how deficient the aircraft becomes when flown close to the boundaries of the flight envelope.

If dual instruction on type is not possible, and there is no one with recent type experience to consult, then a rational analysis of what factors of the aircraft are known (or knowable) will help the pilot to estimate the number and nature of the potential hazards.

“There are known knowns, things we know that we know; and there are known unknowns, things that we know we don't know. But there are also unknown unknowns, things we do not know we don't know.” Donald Rumsfeld.

It is the unknown-unknowns that are the greatest hazard. Therefore, before flying any vintage or replica aircraft for the first time it is essential to identify/quantify all the known-knowns – e.g., trustworthy published data in aircraft manuals inter alia. But even what appears to be ‘certain knowledge’ can be wrong so it is important to avoid over-reliance on a single source of information, wherever possible information should be corroborated using multiple sources.

Then, any remaining recognised gaps in knowledge are 'known-unknowns' e.g. an unknown centre of gravity can be determined by weighing the aircraft, an unknown stalling speed can be estimated and then verified in flight. The pilot should list all the known-unknowns then investigate and research to turn them into known-knowns if possible. If this process is rigorous the number of unknown-unknowns should be minimised.

6.2.1 Low Performance

Modern light aircraft are required to have a minimum rate of climb typically in the region of 400 ft/min whereas some vintage aircraft may only be capable of a 100 ft/min or less and the achievable level flight speed range can be extremely limited also. The pilot of an aircraft with such a low level of performance must consider whether the environmental conditions are suitable for flying as such things as; higher than standard density altitude, wind shear, turbulence or even dew on the wings can prejudice safe flight. See 6.2.7.

6.2.2 Longitudinal characteristics

Parameters which affect the pilot's interaction with the aircraft include longitudinal static stability controls-free, manoeuvre stability controls-free, elevator control power and pitch damping. In all these parameters the horizontal tail volume coefficient is likely to be the largest contributor. Horizontal tail volume coefficient is easily derived as shown in chapter 3 and should be around 0.5 ± 0.15 . If the aircraft has a lower value, the pilot should anticipate deficient handling in one or more of the parameters above. Significantly higher values are probably acceptable although may be a hinderance in aircraft where rapid pitching manoeuvres are required. If the value is low pilots may consider avoiding flight with the centre of gravity towards the rear end of the range until experience has been gained. In addition, the pilot should anticipate that the aircraft may be 'sensitive' in pitch and therefore prone to PIO. The pilot may mitigate this by holding the stick in such a way that the forearm is supported to avoid 'biomechanical feedback' resulting from involuntary hand/arm movements.

6.2.2.1 Longitudinal Instability

If the aircraft is unstable longitudinally this will present itself in one or more ways, in 1g flight the stick force and/or position will not change with airspeed in the accepted stable sense, so an increasing pull force and/or more rearwards stick position may be required as the airspeed increases and vice versa, and, if fitted with a pitch trimming system, it proves impossible to trim the aircraft so that it will not fly hands-off for more than a few seconds. It is quite possible to fly an aircraft which behaves in this way, but more attention is required to maintain airspeed and a safe angle of attack. Flying such an aircraft by sole reference to the flight instruments requires a high workload and is better avoided.

6.2.2.2 Manoeuvre Instability

A more serious deficiency is when the aircraft lacks manoeuvre stability, a measure of which is stick force per 'g'. CS-23 155 specifies a minimum stick force of Weight/140 lbf to reach the limiting load factor – which for an average aircraft weight of weight of 2200 lb is 15.7 lbf and for a typical limit of 4.4 g is $15.7/4.4 = 3.6$ lbf/g. However, some aircraft exhibit less than this and sometimes require a push force to prevent the load factor increasing uncontrollably. If control is released such aircraft will increase load factor, either positive or negative, until structural failure occurs, or the wing stalls. Since both outcomes are undesirable such aircraft are potentially dangerous and require the greatest care to maintain safe flight. If this level of instability is encountered the pilot should restrict the airspeed to less than the manoeuvring speed (V_A) to protect the structure and seek expert advice.

6.2.2.3 Limited Elevator Control Power

If the aircraft exhibits low levels of longitudinal static stability, there should be adequate elevator control power for all normal flight regimes. Assuming a tailwheel configuration, the flight condition that places the greatest demand on elevator control power is the landing; when a full-stall three-point touchdown is the norm – and this condition normally sets the forward centre of gravity limit. When landing, trailing edge flaps will be extended, power will be off, and the aircraft will be in ground effect, all of which usually cause nose-down moments

which must be trimmed by elevator deflection, in addition to the elevator deflection needed to bring the aircraft to the maximum lift coefficient. If, when in the landing configuration with idle power at altitude, it is not possible to reach the aerodynamic stall before the elevator is fully deflected the pilot can anticipate that it will not be possible to achieve that condition when the aircraft is in ground effect prior to touchdown. In such a case the pilot might consider the following mitigations: landing with a reduced flap setting (if that configuration allows the aircraft to reach a full stall), keeping some power on until touchdown (to increase elevator effectiveness), making a wheel landing [provided there is ample propeller ground clearance], or a suitable combination.

6.2.2.4 Low Pitch Damping

Given the low speed, low moments of inertia and low values of relative density of most of the aircraft in the study group, the short period dynamics and low pitch damping is likely to be a secondary consideration. However, the pre-WW2 racing aircraft and the WW2 fighters are fast, relatively dense and typically have lower horizontal tail volume coefficients. Such a combination can result in low pitch damping which may affect the short period pitching response to elevator or bumps. The pilot of such aircraft can expect possible PIO and should avoid aggressive manoeuvring when close to a lift boundary or load factor limit.

6.2.2.5 Effects of Power

All except one of the aircraft in the study are fitted with tractor propellers which may rotate clockwise or anticlockwise according to the design of the engine. Some of the WW1 fighters are fitted with a rotary engine in which the mass of the engine spins with the propeller. In most single engine tractor aircraft, the propeller slipstream affects the dynamic pressure and the direction of the airflow arriving at the horizontal tail. There are several other effects of power which are described in detail earlier and these can have a deleterious effect on the handling qualities. It is sufficient here to point out that the longitudinal stability is compromised in some of the high-performance aircraft, such as racers and fighters, and should a related control difficulty arise it may be mitigated if the pilot makes a power reduction where this is practical.

6.2.2.6 Longitudinal Trim system

Pre-WW1 aircraft are not equipped with a longitudinal trim system so the pilot can expect to have to hold a force to select and maintain any desired pitch attitude. Similarly, some WW1 fighters are without trim system, but a few are equipped with an adjustable tailplane which can work like a pitch trim. Pilots should anticipate that it is usually necessary for the adjustable tailplane to be set to fully trailing edge up to give the sufficient pitch authority to achieve maximum lift coefficient for a three-point landing. But with trim set fully nose up for landing an uncontrollable pitch-up may occur if a high-power setting is used for a go-around. Between WW1 and WW2 longitudinal trim systems took different forms, some used an adjustable spring, others an adjustable tab on the elevator, while the adjustable tailplane was used in some applications. Pilots should understand how the longitudinal trim system in their aircraft operates and recognise that it may not be able to trim the stick force to zero in all combinations of configuration, loading and airspeed.

6.2.3 Directional and Lateral Characteristics

Directional and lateral characteristics have been discussed separately above. Here the guidance to pilots considers those characteristics in their own axes and in combination.

6.2.3.1 Stability

6.2.3.1.1 Directional Instability

The parameters which affect the pilot's interaction with the aircraft are directional static stability controls-fixed and controls-free, rudder control power and yaw damping. In all these parameters the vertical tail volume coefficient is likely to be the largest contributor. Vertical tail volume coefficient is easily derived as shown in chapter 3 and should be around 0.055 ± 0.025 . The vertical tail volume is made up of two components, that from any fixed fin and that provided by the rudder assuming that it is held fixed by some means. The proportions of these two contributions change significantly over the period of study; a few aircraft have no fixed fin, and many have very small fins and relatively large rudders. In these

cases, the rudder contribution is essential for directional stability so that if it is free to trail, the aircraft becomes directionally unstable controls-free. Therefore, the aircraft may not be controllable if the rudder control inceptor is unrestrained or if the rudder becomes fully deflected by other means.

The average value of the entire vertical tail volume coefficient for the 41 aircraft examined was 0.027, just below the minimum and about 50% of the median value recommended for modern aircraft. With the vertical tail volume coefficient at this level the aircraft will likely feel directionally 'loose' to a modern pilot. It is also important to examine the volume coefficient of the fixed fin acting in isolation. The average value of the fixed fin volume coefficient was 0.008 which is just 14% of the average value expected of the vertical tail of a modern aircraft. The pilot must therefore be prepared to act as a full-time yaw stabiliser by restraining the rudder inceptor and, in the worst cases, by actively controlling yaw to prevent excessive sideslips.

Recall that CS 23-177 (a) states '*Static directional stability, as shown by the tendency to recover from a wings level sideslip with the rudder free*'. When static directional stability meets this requirement, the aircraft will turn (change heading) whenever there is a non-zero bank angle without the pilot making a rudder input – the pilot can turn on a single control i.e. aileron. Because of the fin to rudder volume ratio described above, most pre-WW2 aircraft will only be compliant with this requirement if the pilot restrains the rudder. Many will be non-compliant with the rudder free depending on how the propeller slipstream affects the rudder trail angle. Pilots should investigate whether it is possible to turn on a single control with the rudder free. If it is not possible at the initial flight condition it may be possible by at a different combination of power and airspeed.

6.2.3.1.2 Extremes of Lateral Stability

CS 23-177 states that lateral stability is '*shown by the tendency to raise the low wing in a sideslip*' which arises from 'rolling moment due to sideslip' ($C_{l\beta}$) also known as 'dihedral effect'. The rolling moment generated is a function of sideslip which means that the aircraft will roll until sideslip is returned to zero when the rolling moment disappears. This characteristic does not ensure that the aircraft

returns to wings-level although pilots are often told that it will. Although adequate dihedral effect may provide a stable spiral mode that is not that important – what is critical is that in the event of a lateral control system failure the pilot can maintain control of the bank angle using the rudder (able to turn using a single control) and thereby make a survivable landing.

Too little lateral stability might result in an unstable spiral mode and if zero will preclude the ability turn using a single control. Too much lateral stability may compromise aileron roll control at large angles of sideslip.

For vintage aircraft of the sorts examined in this study lateral stability is a function of dihedral angle modified by the height of the wing on the fuselage. Pilots should assess the dihedral angle and wing position to estimate the likely level of lateral stability they might expect. If lateral stability is likely to be absent the pilot will need to recognise that the ‘further effect of rudder’ that they were taught to expect, and in some circumstances rely upon, will not exist.

6.2.3.2 Controllability

6.2.3.2.1 ‘Generous’ Rudder Control Power

Directional static stability causes the aircraft to align itself with the direction of travel thereby minimising sideslip – the stronger the directional stability the greater the yawing moment the rudder must produce to make the aircraft sideslip when this is required. Conversely the weaker the directional static stability the weaker the resistance so the easier it is for the rudder to produce sideslip. Since the greater proportion of the aircraft in the study exhibit low directional static stability, the rudders are more effective than those in modern aircraft. The rudder of a typical biplane from the 1920s-1930s can produce one degree of sideslip angle for one degree of rudder deflection. Given that a typical rudder has thirty degrees of deflection it can generate thirty degrees of sideslip – sometimes with only a modest deflection of the rudder pedal itself and often with little or no pedal force required. When flying a vintage aircraft for the first time in which sideslipping is expected to be used on the approach, the pilot should, at a safe height, ascertain just how much rudder can be used before encountering control over-balance or when the ailerons can no longer maintain lateral control.

6.2.3.2.2 Poor Lateral Control Power or Roll Power

A lateral control system that provides the demanded roll rate without appreciable lag and without objectionable cross-coupling effects such as adverse yaw, are highly valued by pilots. A lateral control system with those characteristics provides a rapid predictable response which facilitates tight roll control for precision tasks such as station keeping in close formation.

While the 1930s monoplane racers and the WW2 fighters in the study group achieve this performance, most vintage aircraft have lateral control characteristics that are far from this ideal. The pilot should assess the lateral control system for expected roll performance in broad terms such as the number, size, placement and aerodynamic balance of the ailerons, and whether refinements in design are incorporated to reduce adverse yaw or modify hinge moments. Some vintage aircraft will be unable to meet the CS 23-157 requirement for a minimum rate of roll of 15 deg/sec in the approach configuration. Pilots should recognise that in aircraft with low lateral control power it may not be possible to recover promptly from lateral upsets encountered in gusty conditions. Furthermore, if the aircraft has a very effective rudder and generous dihedral effect it may not be possible for the pilot to counteract rolling moment due to sideslip if lateral control power is low. Pilots flying aircraft with these characteristics should at a safe height familiarise themselves with the aircraft's lateral controllability when sideslipping.

6.2.3.3 Effects of Power

6.2.3.3.1 Directional

The fin and rudder lie in the spiral slipstream from the propeller and as power is increased the dynamic pressure felt at the tail increases making it more effective and the airflow direction changes producing a yawing moment. Furthermore, asymmetric blade effect imposes a yawing moment with increased power when the aircraft has a high nose attitude and, when the aircraft is sideslipping, the effect of increased power is directionally destabilising through 'fin effect'. (Ribner, 1945) In addition, the gyroscopic precession of pitch rates on the propeller will be precessed into yawing moments. Although increased slipstream makes the fin

and rudder more effective which can be a good thing the other effects can dominate the aircraft and if control becomes difficult the pilot should, if practical in the circumstance, consider reducing power to regain control.

6.2.3.3.2 Lateral

The effect of power on the lateral characteristics is limited to the torque reaction of the rotating engine/propeller which put a rolling moment onto the aircraft. In normal flight this is easily countered by the lateral control although some rotary engine aircraft used a wing tip weight or an aileron modification to provide a moment to oppose a proportion the engine torque. The torque induced rolling moment is rarely noticeable on low powered aircraft. Highly powered WW2 fighters may encounter a 'torque roll' at low airspeed if a sudden increase to full power is demanded. Pilots flying such aircraft should recognise that the maximum power available in these types is intended for a rapid climb to high altitude and for combat and is not needed for a normal takeoff or a go-around. Therefore, pilots should moderate their demanded power when operating at low airspeed and low altitude to avoid a loss of roll control.

6.2.3.3.3 Directional and Lateral Trim system

Directional and lateral trim systems are vanishingly rare in vintage aircraft although rudder trim may be found on twin engine types and powerful WW2 fighters and fighter trainers. The sense of movement of the cockpit trim control should be in the same sense as the aircraft response but this is not always so. Pilots should take care to apply the trim in the correct sense if it mounted in a non-intuitive orientation.

6.2.3.4 Cross coupling effects

6.2.3.4.1 Sideslip Departure

Some aircraft in the pre-WW1 era sideslipped into the ground. This can result if an aircraft which has little directional stability, but generous rudder power coupled with low lateral stability and poor roll control power. Bearing in mind that at that time turns were typically initiated using the rudder, if the aircraft was banked there was a tendency for the bank angle to increase due to rolling moment due to yaw

rate, if this increase in bank angle could not be controlled using the lateral control system (typically wing warping at that time) the pilot would apply opposite rudder to try to stop the turn. The powerful rudder would produce a large sideslip angle but with no lateral stability the aircraft would not roll due to the sideslip. The lateral control inceptor and the rudder would be fully deflected in the same direction. The sideslip would cause significant increase in drag and given the low power engines available then the aircraft would descend in the sideslip until it hit the ground. Back in the day the advice to pilots was to 'rudder into the sideslip' which should remove the sideslip and facilitate recovery. But, if the aircraft was near the stalling angle, as aircraft from that era often were, then 'ruddering in' could precipitate a spin. The sideslip is better avoided so the pilot should recognise the limitation of the lateral control system by only using low bank angles to make turns and to ensure that the rudder is held substantially neutral thereby becoming, or augmenting, the vertical stabiliser to sideslip to a minimum.

6.2.3.4.2 Spiral Dive Departure

As described in Chapter 3 the spiral mode will likely be divergent when the static directional stability is much stronger than the lateral stability. When the aircraft is in a banked turn, the directional stability keeps the aircraft turning and the resulting yaw rate can cause the bank to increase through rolling moment due to yaw rate. If this is greater than the lateral stability the bank angle will continue to increase and typically the pitch attitude will lower until the aircraft is in an ever-tightening descending turn called a 'spiral dive'. Given good lateral control power recovery is straightforward but in the pre-WW1 era lateral control was sometimes absent and often relatively ineffective. Adverse yaw arising from the application of the lateral control for recovery may further contribute to the into-turn yawing moments. Pilots should recognise the limitations of early lateral control systems and avoid using angles of bank from which recovery may be problematic.

6.2.3.4.3 Adverse Yaw

The causes of adverse yaw are discussed in Chapter 3. Pilots should anticipate that adverse yaw may be a significant effect on many vintage aircraft. Originally pilots typically initiated their turns using the rudder, the ailerons being used to

optimise the bank angle for the rate of turn they had demanded with the rudder. This technique avoids creating adverse yaw. However, pilots today expect to roll into a banked turn using aileron and 'co-ordinate' the turn with a rudder input while the ailerons are deflected. If this technique is used in many vintage aircraft significant adverse yaw can be generated particularly when a large aileron deflection is used. Pilots should be prepared to counter adverse yaw with rudder inputs while rolling into and out of banked turns and this is often best achieved by 'leading with the rudder'. In some aircraft surprising large rudder pedal deflections are required for turn coordination when making a full aileron roll input.

6.2.3.4.4 Lateral Control Departure Parameter

This parameter was described in paragraph 3.5.3. If the geometry of the aircraft lends itself to this type of departure it is best avoided by using the rudder rather than aileron to roll the aircraft at low speed/high alpha. Incidentally this technique is used in the 1960's F-4 Phantom II and has proved equally effective in the 1909 Bleriot XI!

6.2.3.4.5 Gyroscopic Precession

The rotating propeller, especially when augmented by a rotary engine, has the properties of a gyroscope. As discussed in Chapter 3 any pitch rate applied to the propeller/engine combination is precessed into a yaw response which can be intrusive when the propeller/engine is rotating rapidly, and the pitch rate is significant. The effect is exacerbated if the directional static stability is low and/or rudder power is low. The best example being the Sopwith Camel described earlier. Pilots should anticipate this effect and, until experience is gained, avoid introducing pitch and yaw rates when the engine is at high RPM. Back in WW1 many inexperienced pilots crashed when making climbing right turns after takeoff. To avoid this possibility the following guidance is offered for a first flight in an aircraft powered by a rotary engine: Climb straight head until at a safe height, reduce power and practice left turns. When proficient in left turns, practice right turns. If control is compromised reduce power.

6.2.4 Control Overbalance

The design and implementation of aerodynamic balance of control surfaces is beyond the scope of this study. When used they are intended to modify control hinge moments and thereby alter the control inceptor forces perceptible to the pilot. In some cases, balanced controls have a tendency for un-demanded movement to full deflection and such behaviour is usually referred to as 'over-balance'. Given the aircraft being discussed are relatively small and relatively slow the reversed hinge moments arising from over-balance can be overpowered by a suitably motivated pilot.

Elevator over-balance is hardly ever encountered which is fortunate since it would have the potential to cause a stall or structural failure. However, pilots should be cautious if they encounter a vintage aircraft fitted with an all-flying tailplane or stabilator as these can suffer from a number of issues which have the potential to compromise safe flight. Aileron over balance is rare but can be disconcerting particularly if the pilot first encounters it while sideslipping on the approach. If the aircraft is fitted with aerodynamically balanced ailerons the pilot should explore the characteristics at a safe height. Rudder over-balance is common in the aircraft from the between WW1 and WW2. If the aircraft has a rudder with aerodynamic balance the pilot should explore the characteristics at a safe height.

6.2.5 Stalling Characteristics

Stalling characteristics are discussed in relation to CS-23 in Chapter 4. For the pilot flying a vintage aircraft for the first time it is important to establish the stall behaviour before attempting a landing – particularly important if a three-point landing is anticipated. Pilots should check that controllability is satisfactory as the stalling condition is approached and identify whether there is adequate warning of the approaching stall. A useful method is to fly a simulated approach to a landing at a safe altitude (c3000 ft agl), after lookout turns set the appropriate approach power (idle in most biplanes) and glide at the estimated best glide airspeed, when ready bring the aircraft to level flight and as the airspeed reduces flare the aircraft steadily to the landing attitude. Maintain the three-point landing attitude until the stall occurs noting the elapsed time between levelling and the

stall. This gives an insight into the amount of float likely during the actual landing and whether there are any surprises e.g., aileron snatch or wing-drop which arise before the simulated 'touch-down'. If such characteristics are encountered a modification to the landing technique may be advisable to avoid a reoccurrence close to the ground. If sideslipping is likely to be needed on the approach, then repeat the exercise but incorporate a slipping turn and a straight steady heading sideslip during the glide before straightening up for the simulated landing. This should be repeated building up the amount of sideslip until either full lateral stick or full rudder pedal deflection is reached – noting which is reached first. Sideslipping in monoplanes is less effective as an approach technique and, on some types, such as the Magister, has proved dangerous in the past so the above investigation is better confined to biplanes.

6.2.6 Slats and Flaps

Up until about 1920 there were no high lift devices. Outboard leading-edge slats were introduced in the early 1920s usually limited to the same spanwise extent as the ailerons. The pilot should not consider these outboard leading-edge slats as a high lift device intended to give the aircraft a lower stalling speed because they were designed only to prevent a wing drop when the aircraft is stalled and thereby reduce likelihood of an unintentional spin. For normal operations they should be free to extend automatically and, if lockable, should only be locked in the retracted position for intentional spinning, aerobatics and in some aircraft types, crosswind landings.

The first generation of trailing edge flaps usually encountered on vintage aircraft of the era of study were intended more as airbrakes to steepen the approach angle than to increase the lift coefficient significantly. Pilots should familiarise themselves with the implementation of any slats and flaps that are fitted to the aircraft and any flight limitations before deployment.

6.2.7 Wind considerations

When a low-speed aircraft manoeuvres at low height in conditions where the ratio of wind speed to aircraft speed is high it will experience large drift angles which

can produce the illusion of significant sideslip, particularly during turns, which may induce the pilot to apply rudder inappropriately thereby risking loss of control. It is recommended that the aircraft is equipped with a slip indicator of a type which the pilot can interpret intuitively.

Wind gradient experienced on the approach to land causes a loss of airspeed as the aircraft approaches the surface and the wind speed reduces rapidly resulting in a loss of lift and an increase in rate of descent. This can affect vintage aircraft to a greater extent because there are generally flown somewhat slower than modern light aircraft. The approach speed scheduled for a modern, nosewheel, aircraft is $1.3V_S$ whereas $1.2V_S$ is more typical with vintage tailwheel types. Even if the stall speeds are identical, the tailwheel type has less airspeed margin, and this is exacerbated for those with low wing loading and hence a lower stall speed. An increment to the approach speed is often necessary to avoid the risk of a heavy landing.

Wind shear i.e. rapid changes in wind speed, can occur in certain weather conditions, and can affect any aircraft by causing sudden changes in airspeed and lift. This effect can be negative, decreasing airspeed and lift or positive. A positive change gives the aircraft more energy, but a negative change has the opposite effect causing airspeed loss and sink. This is rarely an issue for a fast-flying aircraft or those with ample excess power; as the aircraft's momentum can carry it through the transient gust and/or engine power can be increased to counter the sink. But aircraft dating from before WW1 (and the Lympe Trials group) have relatively low momentum, a small airspeed range, and very low power engine. Given that there is low momentum and no additional power available to counter sink a pilot may unconsciously attempt to prevent the sink with a nose-up elevator input, this may reduce the airspeed below minimum power speed (minimum sink speed) thereby exacerbating the sink and if not corrected may result in the angle of attack exceeding the stalling angle with serious consequences at low height. When flying aircraft with these characteristics, if sink is encountered the priority must be to maintain a safe angle

of attack and airspeed which will probably involve making a nose down input and a loss of height.

Aircraft with tail landing gear are directionally unstable when rolling on the ground and are therefore less tolerant to off-axis wind components. To illustrate this point Figure 6-1 shows the surface wind envelope for the nose wheel equipped Scottish Aviation Bulldog, a primary trainer certificated in the 1960's. Its limits are a maximum wind speed of 40 kt, a maximum crosswind component of 30 kt, and a maximum tailwind component of 10 kt.

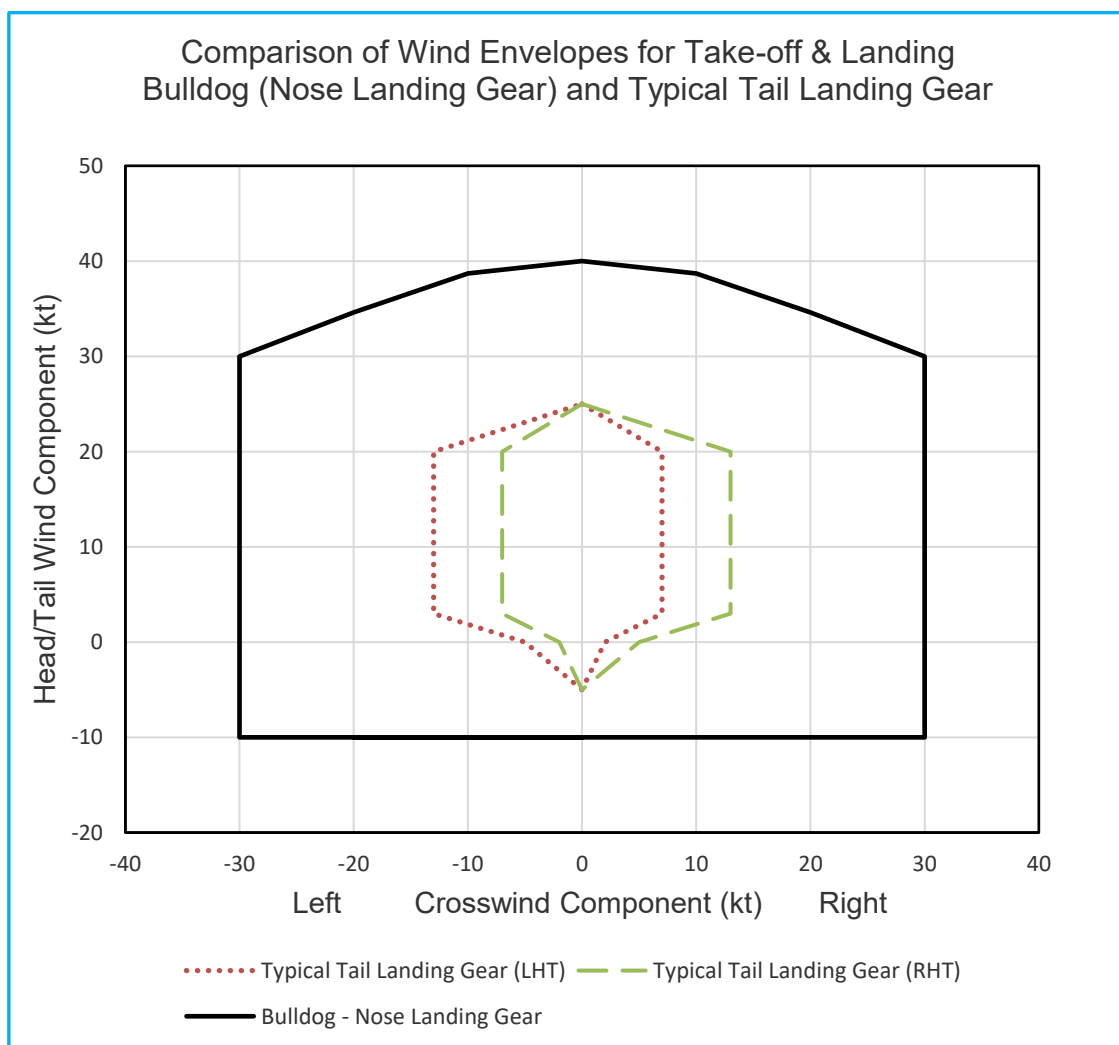


Figure 6-1 – Wind Envelopes for Take-off and Landing

Also shown on in Figure 4-5 are two representative envelopes for typical 1930's light aircraft equipped with tail landing gear. The dashed envelope is for aircraft

with a right-hand tractor propeller and the dotted envelope for an aircraft with a left-hand tractor propeller. Tail landing gear aircraft do not tolerate tailwinds during the landing roll and any cross wind with no headwind component can also threaten directional control; these considerations become even more of a limitation for those vintage aircraft without wheel brakes.

Taxying downwind in an aircraft which has no wheel brakes introduces a threat to directional control if the tail skid is free to castor as any rudder deflection used to steer the aircraft may result in a reversed effect.

Modern pilots accustomed to post WW2 nose-wheel aircraft with wheel brakes may not appreciate the limitations imposed on directional control during take-off, landing and taxying in aircraft with tail landing gear.

7 SUMMARY AND CONCLUSIONS

The handling qualities of aircraft which were designed between the dawn of powered flight and the implementation of rigorous airworthiness codes and certification specifications which came into force following WW2 are likely to be deficient in one form or another. Such deficiencies may not be anticipated or understood by today's pilots who might wish to fly old aircraft and this can result in mishandling, loss of control and ultimately accidents.

7.1 Lessons from the past

7.1.1 Contemporaneous pilot accounts

Until after WW2 little was published in journal papers on aircraft handling qualities to assist the researcher but, by analysing contemporaneous pilot accounts from the earlier years, it has been possible to find qualitative evidence of deficiencies that were then prevalent. Untested hypotheses and myths dominated the discourse among early pilots such as the reversal of control during steep turns. However, from those same accounts certain conclusions are drawn regarding the handling qualities of the aircraft. It's stability or absence of stability in one or more axes, lack of desirable control harmony, absence of trimming devices and the gyroscopic effects of the propeller and rotary engine all added to the challenge of maintaining control of these earlier aeroplanes.

7.1.2 Pilot training methods

Accounts of the training pilots received and extracts from pilot training texts appear to perpetuate some early myths and show how the techniques taught reflected the static directional and lateral stability characteristics of the contemporary training aircraft. From the interpretation of these accounts and published pilot training methods it has been possible to identify the deficiencies in handling qualities which could be used to guide modern pilots away from myths and towards safer and more effective techniques.

7.2 Conclusions from the analysis of surviving aircraft

Alongside the historical review described above an analysis was conducted using a group of 41 mostly British aircraft designed between 1910 and 1950. Longitudinal, directional and lateral stability and control parameters were estimated by using generic equations and aircraft geometry. Calculations were made in a spreadsheet, and the graphical results illustrate trends and highlight aircraft outliers which may have unconventional handling compared to their contemporaries. It must be stressed that the numerical results derived are not claimed to be definitive as no actual measurement of the parameters was possible, they are to be taken as estimates intended to be used only to facilitate comparison with other aircraft in the study group.

7.2.1 Early Birds

It has been shown that in aircraft from before WW1 a large variation of design philosophies results in disparate handling qualities challenges, so much so that an effective technique in one machine may result in a loss of control in another.

7.2.2 First War Birds

During WW1 the imperative to improve performance and simplify production resulted in machines that might be significantly unstable in one or more axes and/or dominated by the torques emanating from their ever more powerful rotary engine and propeller. However, in some designs weight and complication was added to provide better stability and control and a safer machine.

7.2.3 First Ultralights

The handling characteristics of the ultra-light aircraft from 1923-24 Lymington Trials also show significant variation, but they were specially designed for the competition rules and should be viewed as outliers which are not necessarily representative of the general evolution. However, for a modern pilot flying these types the handling qualities deficiencies can prove even more challenging when coupled with poor ergonomics and marginal excess power.

7.2.4 The Biplane Era

While most of the biplanes from the 1920s-1930s era exhibit longitudinal and lateral stability, the controls-free directional stability has been compromised to facilitate sideslipping and out-of-wind taxiing by reducing the ratio of fin to rudder volume. This has a deleterious effect on the handling qualities in normal flight regimes because; it requires considerable pilot compensation to maintain balanced flight, requires a different technique to enter and exit banked turns, and can compromise the ability to maintain safe flight after a rudder control circuit failure. Furthermore, the resulting high rudder effectiveness compromises control harmony and when coupled with the dihedral effect may be capable of producing a greater rolling moment than the lateral control system at lower airspeeds.

7.2.5 Transition to Monoplanes

British industry was slow to accept that the future lay in the monoplane configuration. The first examples retained the over-large rudder and undersized fin because they lacked landing flaps and wheel brakes. Therefore, they require similar flying techniques to the contemporary biplanes and have similar handling qualities deficiencies. As they became capable of higher airspeeds the 'relaxed' controls-free directional stability of their biplane precursors was no longer structurally acceptable and the later examples have proportionally larger fins and equipped with landing flaps, to steepen the approach angle, and wheel brakes to facilitate out-of-wind taxiing. Some of these aircraft were designed for 'racing and record setting' with maximum performance once again being the main consideration. Typically, such aircraft have near neutral longitudinal and lateral stability but are often directionally stable controls-free.

7.2.6 Second War Birds

With the approach of WW2 performance once again drove the development of military aircraft. It was accepted that the ubiquitous multi-role biplanes would never be able to attain the high airspeeds needed. Early WW2 monoplane fighters have much improved controls-free directional static stability but low lateral stability. The horizontal tail design can compromise longitudinal static

stability resulting in a sensitivity in pitch handling which requires skilful piloting if potentially catastrophic pilot induced oscillations are to be avoided. This is the first period in which deficiencies in 'dynamic' stability become a significant concern due to greater inertia and lower rate damping.

7.2.7 Immediate Post WW2

The aircraft flying in the years immediately following WW2 fall into two classes, those of earlier pre-war design, and those designed during or shortly after the war. The earlier types have similar handling qualities to their pre-war ancestors, while the later designs may have benefited from war time research and are likely to have significantly better handling qualities.

7.2.8 'Control Group'

The expansion of aeronautical research that took place during and immediately following WW2 resulted in the development of civil airworthiness requirements and military specifications which codified best practice and prioritised safety over performance. Aircraft designed to comply with these criteria exhibit good open-loop stability and control characteristics and good handling qualities generally.

7.2.9 Specification Compliance

Current certification specifications are used as a benchmark against which the aircraft in this study are assessed for non-compliances [de-facto handling qualities deficiencies] which require pilot compensation to achieve an equivalent level of safety. This analysis showed an inverse linear relationship between year of design of the aircraft and the number of deficiencies it was likely to exhibit. The greater the number of deficiencies in any one aircraft the more challenging it will be to fly.

7.2.10 Other Factors which may affect handling qualities

Other factors including the cockpit interface, and the aircraft environment are known to be very significant in the final assessment of the handling qualities of a given aircraft. An analysis of these factors was made to highlight the higher risk areas when considering the vintage aircraft of the era.

7.2.11 Guidance for modern pilots.

A modern pilot will harbour certain assumptions regarding aircraft stability and control response which may be invalid in vintage aircraft. Drawing on the findings of earlier chapters some areas of guidance to pilots is developed in Chapter 6 which is intended to mitigate some of the handling qualities deficiencies that may be encountered in vintage aircraft.

7.2.12 Answering the research question

The research question was 'To investigate how the evolution of British aircraft handling qualities over the first fifty years of powered flight influenced aircraft development and pilot training methods? To investigate whether knowledge of that evolution can be utilized to improve safety for pilots who fly genuine or replica vintage aircraft today? The investigation demonstrates how the characteristics of the aircraft evolved over the period of study and how these influenced, and were influenced by, aircraft design development in war and peace, and pilot training methods. The findings can be used to provide guidance to a 'modern' pilot who has a requirement to fly a vintage aircraft today and thereby avoid the pitfalls that have claimed many lives in the past.

7.2.13 Limitations

The references used in the study were all in the English language. It is very likely that other material had been published in countries such as France, Germany and Japan which were early aviation pioneers like Britain. The aircraft in the study all fall into what would be classified now as Light Aircraft (<5700kg) because, for reasons of cost, large vintage aircraft such as bombers and transports are rarely preserved and even rarer still, kept airworthy. This fact necessarily imposes a limitation on the scope of the study.

In the analysis of stability and control parameters generic equations were used to estimate a value based on the known aircraft geometry, it is not possible to validate the absolute accuracy of a given result, but the working assumption adopted was that if the same method was used for all the aircraft useful

comparisons could nevertheless be drawn. Therefore, individual values in the analysis should not be taken as definitive.

7.2.14 Possible future work

As in any research process new lines of investigation open-up but are outside the scope of the present work. In this study one area which would benefit from further study is to use standard equations and methods to estimate control hinge moments based on control surface and aerodynamic balance geometry to estimate controls-free stability and control characteristics of the aircraft used in the study.

As the aviation industry moves from fixed wing aircraft with reversible flight control systems towards control-configured vertical take-off and landing vehicles it should be recognised that the Mark 1 human has not evolved at all over this period. If this new wave of flying machines is to be piloted by humans then the lessons learned in the past regarding the way the human interacts with the vehicle and its responses and how they perceive the effectiveness of their control of the vehicle will still apply.

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APPENDICES

Appendix A – UK Aircraft Accidents 1910-1939

UK	Fatal Accidents		Non-Fatal Accidents		Total	
Year	Number	Stall/Spin/ Sideslip/ Loss of Control	Number	Stall/Spin/ Sideslip/ Loss of Control	Number	Stall/Spin/ Sideslip/ Loss of Control
1910	5	0			5	0
1911	5	4			5	4
1912	13	5			13	5
1913	11	4			11	4
1914	23	8			23	8
1915	32	10			32	10
1916	134	50			134	50
1917	528	266			528	266
1918	1133	580			1133	580
1919	111	50	25	4	136	54
1920	13	4	25	1	38	5
1921	18	13	13	2	31	15
1922	23	11	17	3	40	14
1923	31	14	14	2	45	16
1924	37	16	12	0	49	16
1925	34	7	8	1	42	8
1926	45	18	8	1	53	19
1927	37	14	22	2	59	16
1928	48	15	19	4	67	19
1929	35	12	24	3	59	15
1930	49	17	36	9	85	26
1931	54	13	38	9	92	22
1932	41	13	21	2	62	15
1933	47	9	29	5	76	14
1934	48	16	41	5	89	21
1935	49	12	38	2	87	14
1936	71	19	50	4	121	23
1937	120	28	32	3	152	31
1938	132	26	21	10	153	36
1939	288	54	23	4	311	58

Totals	3215	1308	516	76	3731	1384
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Appendix B – A selection of more recent accidents

Extracts from the UK Aircraft Accident Investigation Branch report
De Havilland DH53 Humming Bird, G-EBHX 1 ABC Scorpion II piston engine 1923 (Serial no: 98) 1 July 2012 at 0842 hrs Old Warden Aerodrome, Bedfordshire.(AAIB, 2012)
'The aircraft had, by modern standards, low stability and power margins and poor flight instrumentation. The aircraft was known to be prone to aileron tramping close to the stall and the eyewitness accounts describe a departure from controlled flight consistent with a stall followed by a significant wing drop. It seems likely that the loss of control was the result of a combination of the challenging operating/handling.'
Replica Fokker EIII, G-CHFS EW/C2013/04/02 1 Warner Aircraft Corp Scarab 145 piston engine 2012 (Serial no: LAA 279-14805) 27 April 2013 at 1552 hrs Middle Wallop Airfield, Hampshire.(AAIB, 2013)
Overall, the handling qualities of the aircraft were unusual when compared with modern types and clearly would not comply with modern Requirements (sic). However, having compared reports of the original Eindekker, it appears to be a reasonably authentic representation of how the original Type flew. Also, once experience was gained, the actual flying qualities were reasonably benign as long as the aircraft was flown within the limitations of the wing-warping system.
The comments in the report regarding the controllability of the aircraft were included in the aircraft's pilot's notes that were produced as part of the LAA's permit to fly process. These were also referred to in the LAA's operating limitations document, which stated: 'This aircraft does not comply with modern handling requirements and must not be flown without the pilot having familiarised him/herself with the contents of 'Pilot's Notes Fokker Eindekker EIII Replica G-CHFS 'dated 12/4/13, or in circumstances likely to result in a departure from controlled flight.
When considering operational aspects, the investigation found that, unless attention was paid to the slip indicator, the aircraft could easily enter sideslip without this being obvious to the pilot. Furthermore, should sideslip develop, then roll rates could develop and a roll angle achieved that could not be reversed by the wing-warping roll control system fitted to the aircraft.

DH-82A Tiger Moth, N54556 1 De Havilland Gipsy Major 1H piston engine N/K (Serial no: T-6392RO) 21 July 2019 at 1304 hrs Private airstrip near Hythe, Kent.(AAIB, 2019)

The cause of the accident was the large amount of right rudder applied at high power beyond the limit of full left aileron control. This resulted in a steepening rolling turn to the right with the associated large nose-down pitch attitude and, possibly, an incipient spin.

The test pilot tasked with carrying out an in-flight investigation in another Tiger Moth reported:

In the second sortie, additional rudder was applied having already applied full left aileron. On applying a step input of right rudder, the aircraft promptly rolled right and pitched gently nose-down. The roll rate achieved was in the order of 20° per second which was “uncomfortable”. However, it was easy to recover the aircraft by centralising the rudder and rolling the wings level with aileron. It was evident that if full rudder was applied, the resulting sideslip and the aircraft’s lateral stability would produce a powerful rolling moment to the right that could not be stopped even with the application of full opposite aileron. Both rudder and ailerons tended to float towards neutral when released from modest inputs. However, beyond 70% right rudder travel, the rudder would remain applied with no tendency to centralise without the pilot’s intervention. Additionally, with the rudder free to move and climb power applied, the rudder would gently migrate towards full right rudder deflection without any assistance from the pilot.

Replica Royal Aircraft Factory BE2c, G-AWYI 1 De Havilland Gipsy Major Mk 10-1 piston engine 1969 (Serial no:1) 2 September 2020 at 1038 hrs Sywell Aerodrome, Northamptonshire.(AAIB, 2020)

The pilot was experienced at flying this aircraft and did not think that he simply stalled the aircraft in the turn. However, the aircraft requires quite low stick force to stall, the stick does not need to come fully aft and there is no marked stall warning. It is possible that whilst manoeuvring the aircraft slightly aggressively the pilot inadvertently stalled the aircraft. The adverse aileron yaw requires quite large rudder inputs to maintain balanced flight particularly if large aileron inputs are used. It is possible that this led to the aircraft being out of balance in the turn. The small fin and large rudder means that it is quite easy to generate large sideslip angles and yaw rates. This would lead to a spin if the aircraft was stalled. The aircraft was not fitted with leading edge slats which are fitted to the Tiger Moth to help reduce the aircraft’s tendency to enter a spin when a wing drops at the stall.

Appendix C - Aircraft in the study

This appendix contains images of the aircraft which were analysed in the study to illustrate their layout and show any salient characteristics which influence their handling qualities, stability or controllability. The aircraft are grouped as they are in the graphs in Chapter 3.

Pre WW1 - Biplanes

Roe Triplane IV - 1910



This aircraft has a symmetrical tailplane of generous size with smaller elevator hinged from it. There is no trim system. There is no fixed vertical stabiliser, only a rudder. Warping the top two wings provides lateral control. There is no dihedral. This is a reproduction built in the 1960's and is

fitted with a later Cirrus Hermes engine which provides more power than the original.

Bristol Boxkite - 1910



This aircraft has a cambered biplane tailplane (lifting tail) of generous size with smaller elevator hinged from the top surface and linked to a front elevator. There is no trim system. The 1910 original had no vertical stabiliser and two rudders. Four 'balancers'

(single acting ailerons) are fitted to upper and lower wings. There is no dihedral. This is a reproduction built in the 1960's, a fixed vertical stabiliser has been added and a third rudder. In addition, it is fitted with a Rolls Royce Continental O-200 engine which is thought to provide equivalent thrust to the original 50HP Gnome rotary.

Pre WW1 - Monoplanes

Bleriot XI - 1909



This aircraft has a relatively small fixed, cambered tailplane (lifting tail). The outer portions pivot to form elevators. There is no trim system. There is no fixed vertical stabiliser, only a rudder. Warping the wings provides lateral control. There

is generous dihedral and a high wing. Anzani fan engine of c 25 BHP.

Deperdussin - 1910



This aircraft has a generous, cambered tailplane (lifting tail) with elevator hinged at the rear. There is no trim system. There is a small vertical stabiliser, and a much larger rudder. Warping the wings provides lateral control. There is no dihedral

on the shoulder mounted wing. Anzani Y engine of c 30 BHP.

Pre WW1 - Monoplanes (continued)

Blackburn - 1912



This aircraft has a symmetrical tailplane of generous size with smaller elevator hinged from it. There is no trim system. There is a generous fixed vertical stabiliser, and larger rudder. Warping the wings provides lateral control.

There is modest dihedral. 50 BHP Gnome rotary engine.

WW1 Fighters - Biplanes

Avro 504K - 1914



This aircraft has a symmetrical tailplane of generous size with smaller elevator hinged from it. There is no trim system. There is no fixed vertical stabiliser, only a 'balanced' rudder. Ailerons on all wings provide lateral control. There is suitable dihedral. 110 BHP

Rhone rotary engine.

WW1 Fighters - Biplanes (continued)

Sopwith Pup - 1916



This aircraft has a symmetrical tailplane of generous size with smaller elevator hinged from it. There is no trim system. There is a small fixed vertical stabiliser, and a much larger rudder. Ailerons on all wings provide lateral control. There is suitable dihedral. 80 BHP

Rhone rotary engine.

Sopwith Triplane - 1916



This aircraft has an adjustable tailplane of modest area with smaller elevator hinged from it. There is a small fixed vertical stabiliser, and a much larger rudder. Ailerons on all wings provide lateral control. There is suitable dihedral. This is a

faithful reproduction fitted with an original 130 BHP Clerget rotary engine.

WW1 Fighters - Biplanes (continued)

Sopwith Camel - 1917



This aircraft has a symmetrical tailplane of small area with smaller elevator hinged from it. There is no trim system. There is a small fixed vertical stabiliser, and rudder of double the size of the fin. Ailerons on all wings provide lateral control. There is generous dihedral on the lower

wing only. This is a faithful reproduction fitted with an original 130 BHP Clerget rotary engine.

Bristol Fighter F2b - 1917



This aircraft has an adjustable tailplane of generous area with larger elevator hinged from it. There is a modest vertical stabiliser, and smaller rudder. Ailerons on all wings provide lateral control. There is suitable dihedral on both wings. 275 BHP Rolls Royce Falcon III

engine.

WW1 Fighters - Biplanes (continued)

Royal Aircraft Factory SE5a - 1917



This aircraft has an adjustable tailplane of generous area with larger elevator hinged from it. There is a large vertical stabiliser, and rudder of similar dimensions. Ailerons on all wings provide lateral control. There is suitable dihedral on both wings. 200 BHP Wolseley

Viper engine.

WW1 Fighters - Monoplane

Bristol M1c - 1917



This aircraft has a symmetrical tailplane of large area with larger elevator hinged from it. There is no trim system. There is a large vertical stabiliser, and smaller rudder. Ailerons provide lateral control. There is modest dihedral and a shoulder mounted wing. This is a faithful reproduction fitted

with an original 110 BHP Rhone rotary engine.

Lympne Trials 1923-24 - Biplanes

Hawker Cygnet - 1924



This aircraft has a symmetrical tailplane of generous area with same sized elevator hinged from it. There is no trim system. There is no vertical stabiliser, only a rudder. Single acting ailerons on all wings provide lateral control which can also be 'drooped' as flaps. There is no dihedral. This is a

faithful reproduction fitted with a post-WW2 Mosler engine of 35 BHP.

Lympne Trials 1923-24 - Monoplanes

English Electric Wren - 1923



This aircraft has a symmetrical tailplane of generous area with slightly smaller elevator hinged from it. There is no trim system. There is a modest vertical stabiliser, and a much larger rudder. Ailerons provide lateral control. There is no dihedral, but it has a high wing.

It is fitted with an All British (Engine) Company engine of 8 BHP.

Lympne Trials 1923-24 – Monoplanes (continued)

de Havilland DH-53 Humming Bird – 1923



This aircraft has a symmetrical tailplane of generous area with much larger elevator hinged from it. There is no trim system. There is a very small vertical stabiliser, and a much larger rudder. Ailerons provide lateral control. There is

suitable dihedral. A.B.C. Scorpion II engine of 34 BHP.

Air Navigation & Engineering Company (ANEC) II - 1924



This aircraft has a symmetrical narrow chord tailplane with a much larger elevator hinged from it. There is no trim system. There is a small, narrow-chord vertical stabiliser, and a much larger rudder. Ailerons provide lateral control. There is modest

dihedral and a high wing. A.B.C. Scorpion II engine of 34 BHP.

1920s-1930s Biplanes

de Havilland DH-51 Moth – 1925



This aircraft has a symmetrical tailplane with the elevator of equivalent area hinged from it. There is spring bias trim system. There is a very small fixed vertical stabiliser, and a very much larger rudder. Ailerons on the lower wings only provide lateral control. There is

modest dihedral. ADC Airdisco engine of 120 BHP.

de Havilland DH-60 Cirrus Moth – 1925



This aircraft has a symmetrical tailplane with the elevator of similar area hinged from it. There is spring bias trim system. There is a very small fixed vertical stabiliser, and a very much larger rudder. Ailerons on the lower wings only provide lateral control. There is

modest dihedral. ADC Cirrus III engine of 90 BHP.

1920s-1930s Biplanes (continued)

de Havilland DH-60X Hermes Moth – 1928



This aircraft has a symmetrical tailplane with the elevator of similar area hinged from it. There is a spring bias trim system. There is a very small fixed vertical stabiliser, and a very much larger rudder. Ailerons on the lower wings only provide lateral control. There is modest

dihedral. Slats are fitted to the top wing. Cirrus Hermes II engine of 105 BHP.

Hawker Tomtit – 1928



This aircraft has an adjustable tailplane with a smaller elevator hinged from it. There is a modest fixed vertical stabiliser, and a very much larger rudder. Ailerons on the lower wings only provide lateral control. There is very little dihedral. Armstrong

Siddeley Mongoose IIIc engine of 150 BHP.

1920s-1930s Biplanes (continued)

Polikarpov Po-2 – 1928



This aircraft has a symmetrical tailplane with a smaller elevator hinged from it. There is a trim tab. There is a small fixed vertical stabiliser, and a very much larger rudder. Ailerons on all the wings provide lateral control. There is modest dihedral. Shvestov M11D

engine of 125 BHP.

Parnall Elf – 1929



This aircraft has an adjustable tailplane with a similar sized elevator hinged from it. There is also a spring bias trim system. There is a very small fixed vertical stabiliser, and a very much larger rudder. Ailerons on the upper wings only provide lateral control. There is modest dihedral and a

small wing sweep angle. Cirrus Hermes II engine of 105 BHP.

1920s-1930s Biplanes (continued)

Avro Tutor – 1929



This aircraft has an adjustable tailplane of very generous area with a larger elevator hinged from it. There is a small fixed vertical stabiliser, and a very much larger rudder. Ailerons on all the wings provide lateral control. There is modest dihedral. Slats are fitted to the top wing. Wheel brakes are fitted. Armstrong Siddeley Lynx IVC

engine of 240 BHP.

Southern Aircraft Ltd Martlet – 1930



This aircraft has a symmetrical tailplane with a smaller elevator hinged from it. There is no trim system. There is a small fixed vertical stabiliser, and a much larger rudder. Ailerons on all the wings provide lateral control. There is very little dihedral. Armstrong Siddeley Genet Major

engine of 105 BHP.

1920s-1930s Biplanes (continued)

de Havilland DH-82a Tiger Moth – 1931



This aircraft has a symmetrical tailplane with a larger elevator hinged from it. There is a spring bias trim system. There is a very small fixed vertical stabiliser, and a very much larger rudder. Ailerons on the lower wings only provide lateral control. There is a modest dihedral and a small wing

sweep angle. Slats are fitted to the top wing. Gipsy Major Mk 1 engine of 130 BHP.

Hawker Hind – 1934



This aircraft has an adjustable tailplane of generous area with a smaller elevator hinged from it. There is a small fixed vertical stabiliser, and a very much larger rudder. Ailerons on the upper wings only provide lateral control. There is a modest dihedral. Slats are fitted to the top wing. Wheel

brakes are fitted. Rolls Royce Kestrel V engine of 640 BHP.

1920s-1930s Biplanes (continued)

Gloster Gladiator Mk 1 - 1935



This aircraft has an adjustable tailplane of generous area with a slightly larger elevator hinged from it. There is a moderately sized fixed vertical stabiliser, and a much larger rudder. Ailerons on all the wings provide lateral control. There is modest dihedral. Split flaps and wheel

brakes are fitted. Bristol Mercury XXX engine of 840 BHP.

Blackburn B2 – 1936



This aircraft has a symmetrical tailplane with a larger elevator hinged from it. There is spring bias trim system. There is a small fixed vertical stabiliser, and a much larger rudder. Ailerons on the lower wings provide lateral control. There is a small dihedral angle. Slats are fitted

to the top wing. Gipsy Major Mk 1 engine of 130 BHP.

1930s-1940s - Civilian Monoplanes

Comper Swift – 1929



This aircraft has a symmetrical tailplane of modest area with a smaller elevator hinged from it. There is no trim system. There is a small high aspect ratio fixed vertical stabiliser, and a slightly larger rudder. Ailerons provide lateral control. There is no dihedral but has a high wing. Pobjoy R engine of 75 BHP.

Desoutter Mk 1 - 1930

This aircraft has a symmetrical tailplane of modest area with a smaller elevator



hinged from it. There is an elevator trim tab. There is a small low aspect ratio fixed vertical stabiliser, and a rudder of twice the area. Ailerons provide lateral control. There is no dihedral but has a high wing. Cirrus Hermes II engine of 105 BHP.

1930s-1940s - Civilian Monoplanes (continued)

Miles Hawk Speed Six – 1934



This aircraft has a symmetrical tailplane of generous area with a smaller elevator hinged from it. There is a spring bias trim system. There is a small triangular fixed vertical stabiliser, and a somewhat larger rudder. Ailerons provide lateral

control. There is a small dihedral angle. Split flaps and wheel brakes are fitted. de Havilland Gipsy Six 1F of 200 BHP.

Percival Mew Gull – 1934



This aircraft has a symmetrical tailplane of small area with a much smaller elevator hinged from it. There is an elevator trim tab. There is a very small fixed vertical stabiliser, and a rudder of twice the area. Ailerons provide lateral control. There is a small dihedral angle. Split flaps and wheel brakes

are fitted. de Havilland Gipsy Six 1 of 200 BHP.

1930s-1940s - Civilian Monoplanes (continued)

de Havilland DH-88 Comet – 1934



This aircraft is fitted with a sharply tapering wing planform and has a symmetrical tailplane of small area with a significantly larger elevator hinged from it. There is a spring bias trim system. There is a modest fixed vertical stabiliser, and a somewhat larger rudder. Ailerons provide lateral

control. There is a modest dihedral angle. Split flaps and wheel brakes are fitted. Two de Havilland Gipsy Six 1 engines of 200 BHP each.

Miles Magister – 1937



This aircraft was a military development of the civilian 1934 Hawk Trainer. It has a symmetrical tailplane of ample area with a similarly sized elevator hinged from it. There is an elevator trim tab. There is a tiny vertical stabiliser, and a rudder of seven times the area..

Ailerons provide lateral control. There is a modest dihedral angle. Split flaps and wheel brakes are fitted. Gipsy Major Mk 1 engine of 130 BHP.

1930s-1940s - Military monoplanes

Westland Lysander – 1939



This aircraft has an adjustable symmetrical tailplane of ample area with a much larger elevator hinged from it. There is a moderately sized fixed vertical stabiliser, and a slightly smaller rudder. Ailerons provide lateral control. There is a small dihedral angle and a high wing. Full

span slats, trailing edge flaps and wheel brakes are fitted. Bristol Mercury XX engine of 785 BHP.

Hawker Sea Hurricane – 1941



This aircraft has a modest symmetrical tailplane with a smaller elevator hinged from it. There is an elevator trim tab. There is a moderately sized fixed vertical stabiliser, and a rudder of nearly twice the area. Ailerons provide lateral control. There is a modest

dihedral angle. Split flaps and wheel brakes are fitted. Rolls Royce Merlin III engine of 1030 BHP.

1930s-1940s - Military monoplanes (continued)

Vickers-Supermarine Spitfire LFVc – 1942



This aircraft has a modest symmetrical tailplane with a smaller elevator hinged from it. There is an elevator trim tab. There is a moderately sized fixed vertical stabiliser, and a rudder of twice the area. Ailerons provide lateral control. There is moderate dihedral. Split

flaps and wheel brakes are fitted. Rolls Royce Merlin 45 engine of 1440 BHP.

Post WW2 - Monoplanes (with tail landing gear)

Avro XIX Anson – 1946



This aircraft has a large area symmetrical tailplane with a much smaller elevator hinged from it. There is an elevator trim tab. There is a moderately sized fixed vertical stabiliser, and a rudder of twice the area. Ailerons provide lateral control. There is moderate dihedral.

Split flaps and wheel brakes are fitted. Two Armstrong Siddeley Cheetah 17 engines of 385 BHP each.

Piper PA-18 Cub – 1949



This aircraft has a symmetrical tailplane with a smaller elevator hinged from it. Pitch trim is provided with the adjustable tailplane. There is a moderately sized fixed vertical stabiliser, and a larger rudder. Large ailerons

provide lateral control. There is no dihedral but has a high wing. Trailing edge flaps and wheel brakes are fitted. Lycoming O-320 of 150 BHP.

Post WW2 - Monoplanes (with tail landing gear) (continued)

de Havilland Canada DHC-1 Chipmunk – 1952



This aircraft has a generous symmetrical tailplane with a similarly sized elevator hinged from it. There is an elevator trim tab. There is a moderately sized fixed vertical stabiliser, and a somewhat larger rudder. Ailerons provide lateral control. There is

moderate dihedral. Trailing edge flaps and wheel brakes are fitted. Gipsy Major 10 engine of 145 BHP.

Percival Provost TMk1 – 1950



This aircraft has a generous symmetrical tailplane with a smaller elevator hinged from it. There is an elevator trim tab. There is a moderately sized fixed vertical stabiliser, and a similarly sized rudder. Large ailerons provide lateral control. There is moderate dihedral. Trailing edge

flaps and wheel brakes are fitted. Alvis Leonides 126 engine of 550 BHP.

1960s-1970s - Monoplanes (with nose landing gear)

The aircraft in this last group demonstrate how such handling characteristics changed following the renaissance effected by WW2 research and development subsequently trickling down into general aviation types. They do not form part of the study period per se, but their stability and control parameters have also been derived to provide a standard against which the earlier generations of aircraft can be compared.

Cessna 182 Skylane



This aircraft has a generous symmetrical tailplane with a relatively small elevator hinged from it. There is a large fixed vertical stabiliser, and rudder of half the area. Ailerons provide lateral control. There is very little

dihedral but has a high wing. Trailing edge flaps, nosewheel steering and wheel brakes are fitted. Lycoming IO-540-AB1A5 engine of 230 BHP.

Piper PA-28 Cherokee



This aircraft has a generous horizontal stabilator (all flying tail). There is a large fixed vertical stabiliser, and a rudder of half the area. Ailerons provide lateral control. There is generous dihedral. Trailing edge flaps and wheel brakes are fitted. Lycoming O-320-E2A engine of 150 BHP.

1960s-1970s - Monoplanes (with nose landing gear) (continued)

Sia Marchetti 260



This aircraft has a generous symmetrical tailplane with a much smaller elevator hinged from it. There is a large fixed vertical stabiliser and dorsal, and a rudder of 70% of the fin area. Ailerons provide lateral control. There is generous dihedral. Trailing edge flaps, nosewheel steering and

wheel brakes are fitted. Textron Lycoming O-540-E4A5 engine of 260 BHP.

Fuji FJ-200



hinged from it. There is a large fixed vertical stabiliser, and a similarly sized rudder. Ailerons provide lateral control. There is very generous dihedral. Trailing edge flaps, nosewheel steering and wheel brakes are fitted. Textron Lycoming IO-360B1B engine of 180 BHP.

1960s-1970s - Monoplanes with nose landing gear (continued)

Gruman GA-7 Cougar



This aircraft has a generous symmetrical tailplane with a smaller elevator hinged from it. There is a large fixed vertical stabiliser and dorsal fin, and a small rudder of 80% of the fin area. Ailerons provide lateral control. There is generous

dihedral. Trailing edge flaps, nosewheel steering and wheel brakes are fitted. Two Textron Lycoming O-320-D1D engines of 160 BHP each.

Appendix D – Calculations and Equations

Generic Data				
ID	Parameter		Units	Notes
ρ	MSL Density	0.00237	slug/ft ³	
g	MSL Gravity	32.2	ft/sec ²	
q_w	Dynamic pressure	$= \frac{1}{2} \rho V^2$		
q_T	Dynamic pressure at tail	$= 0.75 q_w$		Assumption
η_T	Tail efficiency	$= q_w / q_T$		= 0.75
Wt	Weight		lbf	
M	Mass		slug	
	Mol		slug/ft ²	
μ	Relative density	$= M / (S_w \cdot b_w)$		
BHP	Engine power		BHP	
	Power loading	$= Wt / BHP$		
V_{S1g}	1g Stalling speed		ft/sec	
V_H	Max level speed		ft/sec	

Longitudinal				
Wing Parameters				
ID	Parameter	Equation	Units	Notes
b_{uw}	Wingspan (upper)		ft	
b_{lw}	Wingspan (lower)		ft	
b_w	Mean wingspan	$= (b_{uw} + b_{lw}) / 2$	ft	
c_w	Chord		ft	
c_T	Tip chord		ft	
c_R	Root chord		ft	
S_w	Wing area		ft ²	
	Wing stagger		ft	
	Wing volume	$= c_w \cdot S_w$	ft ³	
G	Gap (biplane)		ft	
	Gap/Mean wingspan ratio	$= G / b_w$	-	
k	Munks span factor	$= \sqrt{[1.8 \cdot (G / b_w) + 1]}$	-	
A_w	Aspect ratio	$= b_w / S_w$	-	
λ	Taper ratio	$= c_T / c_R$	-	
a_w	Lift curve slope	$= f(A_w)$	1/rad	

	function $A < 6$	$= -0.0016(A_W)^2 + 0.0243A_W - 0.0152$	$1/rad$	
	function $A > 6$ biplane	$= \frac{1.65 \cdot \pi \cdot A_W}{(A_W + 2)}$	$1/rad$	
	function $A > 6$ monoplane	$= \frac{2 \cdot \pi \cdot A_W}{(A_W + 2)}$	$1/rad$	
Tailplane Parameters				
b_T	Span		ft	
c_T	Chord		ft	
S_T	Area		ft ²	
l_T	Tailplane arm		ft	
	Tailplane volume	$= l_T \cdot S_T$	ft ³	
	Tailplane to wing area ratio	$= S_T / S_W$	-	
$\bar{V}_T$	Tailplane volume coefficient	$= (l_T \cdot S_T) / (c_W \cdot S_W)$	-	
Elevator Parameters				
b_E	Elevator span		ft	
c_E	Elevator chord		ft	
S_E	Elevator area		ft ²	
l_E	Elevator arm		ft	
	Elevator volume	$= l_E \cdot S_E$	ft ³	
S_{HT}	Horizontal tail area	$= S_T + S_E$	ft ²	
	Elevator to horizontal tail area	$= S_E / S_{HT}$	-	
τ_E	Elevator effectiveness	$= f(S_E / S_{HT})$	-	
	function	$\tau_E = \left(-0.6116 \left(\frac{S_E}{S_{HT}} \right)^2 \right) + \left(1.509 \frac{S_E}{S_{HT}} \right) + 0.0704$		
$\bar{V}_E$	Elevator volume coefficient	$= (l_E \cdot S_E) / (c_W \cdot S_W)$	-	
	Elevator to tailplane volume ratio	$= \bar{V}_E / \bar{V}_T$	-	
Complete Horizontal Tail Parameters				
b_{HT}	Span		ft	
c_{HT}	Chord		ft	
S_{HT}	Area	$= S_T + S_E$	ft ²	
A_{HT}	Aspect ratio	$= (b_{HT}^2) / S_{HT}$	-	
a_{HT}	Lift curve slope	$= f(A_{HT})$	$1/rad$	

	function	$a_{HT} = \pi \cdot A_{HT} / \sqrt{1 + (A_{HT}/2)^2}$		
l_{HT}	Tail arm		ft	
	Horizontal tail volume	$= l_{HT} \cdot S_{HT}$	ft ³	
	Horizontal tail to wing area ratio	$= S_{HT} / S_W$	-	
$\bar{V}_{HT}$	Horizontal Tail volume coefficient	$= (l_{HT} \cdot S_{HT}) / (c_W \cdot S_W)$	-	
η_{HT}	Tail efficiency	$= q_{HT} / q_W$	-	
$d\varepsilon/d\alpha$	Downwash	$= a_W \cdot (114.6 / \pi \cdot A_W)$		
dC_M/dC_L HT	Horizontal tail contribution to longitudinal static stability	$= -\frac{a_{HT}}{a_W} \cdot V_{HT} \cdot \eta_{HT} \cdot \left(1 - \frac{d\varepsilon}{d\alpha}\right)$		
dC_M/dC_L TO	Fixed tailplane contribution to longitudinal static stability	$= -\frac{a_{HT}}{a_W} \cdot V_{TO} \cdot \eta_{HT} \cdot \left(1 - \frac{d\varepsilon}{d\alpha}\right)$		
	Contribution to dC_M/dC_L of fixed elevator	$= (dC_M/dC_L)_{HT} - (dC_M/dC_L)_{TO}$	1/rad	
$C_M \delta_E$	Elevator control power	$= -a_{HT} \cdot \bar{V}_{HT} \cdot \eta_{HT} \cdot \tau_E$		
$C_M q$	Pitch damping	$= -1.1 \cdot a_{HT} \cdot V_{HT} \cdot \eta_{HT} \cdot \left(\frac{l_{HT}}{c_W}\right) \cdot \left(\frac{1}{\mu}\right)$		

Directional				
Fin Parameters				
ID	Parameter	Equation	Units	Notes
b_F	Height		ft	
c_F	Chord		ft	
S_F	Area		ft ²	
l_F	Fin arm		ft	
	Fin volume	$= l_F \cdot S_F$	ft ³	
	Fin to wing area ratio	$= S_F / S_W$	-	
$\bar{V}_F$	Fin volume coefficient	$= (l_F S_F) / (b_W \cdot S_W)$	-	
Rudder Parameters				
b_R	Height		ft	
c_R	Chord		ft	
S_R	Rudder area		ft ²	
l_R	Rudder arm		ft	
	Rudder volume	$= l_R \cdot S_R$	ft ³	
	Rudder to wing area ratio	$= S_R / S_W$	-	
S_{VT}	Vertical tail area	$= S_F + S_R$	ft ²	
	Rudder to vertical tail area	$= S_R / S_{VT}$	-	
	Rudder to fixed fin area ratio	$= S_R / S_F$		
τ_R	Rudder effectiveness	$= f(S_R / S_{VT})$	-	
$\bar{V}_R$	Rudder volume coefficient	$= (l_R \cdot S_R) / (b_W \cdot S_W)$	-	
	Rudder to fixed fin volume ratio	$= \bar{V}_R / \bar{V}_F$		
Complete Vertical Tail Parameters				
b_{VT}	Span		ft	
c_{VT}	Chord		ft	
S_{VT}	Area	$= S_F + S_R$	ft ²	
A_{VT}	Aspect ratio	$= 1.55(b_{VT}^2) / S_{VT}$	-	
a_{VT}	Lift curve slope	$= f(A_{VT})$	1/rad	
	function	$a_{VT} = (-0.0024A_{VT}^2) + (0.0262A_{VT})$		
l_{VT}	Tail arm		ft	
	Vertical tail volume	$= l_{VT} \cdot S_{VT}$	ft ³	
	Vertical tail to wing area ratio	$= S_{VT} / S_W$	-	

$\bar{V}_{VT}$	Vertical tail volume coefficient	$= (l_{VT} \cdot S_{VT}) / (b_W \cdot S_W)$	-	
η_{VT}	Tail efficiency	$= q_{VT} / q_W$	-	
	Sidewash	Not considered		
$dC_N/d\beta_{VT}$	Vertical tail contribution to directional static stability	$= a_{VT} \cdot \bar{V}_{VT} \cdot \eta_{VT}$	1/rad	
$dC_N/d\beta_{FO}$	Fixed fin only contribution to directional static stability	$= a_{VT} \cdot \bar{V}_F \cdot \eta_{VT}$	1/rad	
	Contribution to $dC_N/d\beta$ of fixed rudder	$= (dC_N/d\beta)_{VT} - (dC_N/d\beta)_{FO}$	1/rad	
$C_N \delta_R$	Rudder control power	$= -a_{VT} \cdot \bar{V}_{HT} \cdot \eta_{HT} \cdot \tau_R$		
	Rudder sensitivity	$= C_N \delta_R / 57.3 \cdot \frac{dC_N}{d\beta}$		
C_{Nr}	Yaw damping	$= -1.1 a_{HT} \cdot V_{HT} \cdot \eta_{HT} \cdot \left(\frac{l_{HT}}{c_W} \right) \cdot \left(\frac{1}{\mu} \right)$		

Lateral				
Wing Parameters				
ID	Parameter	Equation	Units	Notes
Γ	Wing dihedral		deg	
h	Wing position	High = 2, Shoulder = 1, Mid/Biplane= 0, Low = -2	deg	
Γ_{Eff}	Effective dihedral	$= \Gamma + h$	deg	
$S\Gamma$	Area of wing with dihedral		ft ²	
$\bar{y}$	Quarter span	$= b_W/4$	ft	
$dC_l/d\beta$	Rolling moment due to beta	$= -2 \cdot \Gamma_{Eff} \cdot a_W \cdot \left(\frac{\bar{y}}{b_W}\right) \cdot \left(\frac{S\Gamma}{S_W}\right)$	1/deg	
Aileron Parameters				
n_A	Number of			
b_A	Aileron span		ft	
c_A	Aileron chord		ft	
S_A	Area of aileron	$= b_A \cdot c_A$	ft ²	
ΣS_A	Total aileron area	$= S_A \cdot n_A$	ft ²	
	Aileron to wing area ratio	$= \Sigma S_A / S_W$	-	
k_1	Inboard end		ft	
k_2	Outboard end		ft	
l_A	Aileron arm	$= (b_A/2) + k_1$	ft	
	Aileron volume	$= \Sigma S_A \cdot l_A$	-	
V_A	Aileron volume coefficient	$= (\Sigma S_A \cdot l_A) / (S_W \cdot b_W)$	-	
	Aileron to wing chord ratio	$= c_A / c_W$	-	
τ_A	Effectiveness	$= f(c_A/c_W)$	-	
	function	$\tau_A = 1.4755(c_A/c_W)^{0.6671}$	-	
$C_l \delta_A$	Aileron power	$= \frac{n_A \cdot a_W \cdot \tau_A}{S_W \cdot b_W} \int_{k_1 b_W/2}^{k_2 b_W/2} cy \, dy$		
C_{lp}	Roll damping	$= f(A_W)$		
	function	$C_{lp} = (-0.001A_W^2) + (0.0418A_W) + 0.2775$		
C_{lr}	Roll moment due to yaw rate	$= C_L/4 \text{ or } C_L/6$	1/rad	
	Spiral criteria	$= (C_l \beta \cdot C_N r) - (C_N \beta \cdot C_l r)$		

Appendix E - The significance of landing gear layout

E.1 General

The design of the landing gear can have a very significant influence on the handling qualities of an aircraft during taxiing, take-off and landing. This section expands on those characteristics.

The term 'landing gear'* refers to the devices which carry the weight of the aircraft when it is on the ground, and which may allow the aeroplane to move about on the surface under its own power or under tow.

- Landing gear may refer to wheels, floats or skids or be a combination of these. In the UK in the past, it has been referred to as the 'undercarriage' or the 'chassis', probably reflecting earlier modes of surface transport, but landing gear is now in universal use.

Except for a few specialist applications, most fixed wing landplanes, designed since WW2, are equipped with a 'tricycle' landing gear. Tricycle landing gear consists of the main wheels, carrying the greater proportion of the weight, set somewhat behind the aircraft's centre of gravity, with a nose wheel located ahead, so arranged so that the longitudinal axis of the aircraft is substantially horizontal when the aircraft is sitting on its wheels on the ground. This type of landing gear offers many advantages which make for good ground handling qualities except perhaps on very rough or soft surfaces. These advantages include inter alia,

- Good forward field of view which enables the pilot to avoid obstacles when taxiing and to see the runway during take-off, approach and landing.
- Inherent directional dynamic stability – meaning that the aircraft has a natural tendency to align itself with its ground path – in the same way a wheeled trailer will follow behind its tow vehicle without control action by the driver.
- Tendency to reduce angle of attack on mainwheel contact at touchdown reducing significantly the likelihood of bouncing.

- Simple directional control on the ground through by a suitable arrangement which provides direct nose wheel steering.

Since the wheels do not offer much rolling resistance, and the level attitude on the ground gives minimum aerodynamic drag, all tricycle aircraft rely on wheel brakes for stopping after landing.

However, with a very few exceptions, virtually all aircraft designed between 1910 and 1945 had 'conventional' landing gear. The nose high/tail low inclination of the aircraft's longitudinal axis when sitting on these three points is often close to the stalling angle of the wing. From this it follows that when a landing is made in the so called 'three-point attitude' where main gear and tail gear touch down simultaneously the aircraft will be very close to the wings stalling angle and therefore will be at the minimum possible airspeed as it lands resulting in the shortest possible landing run. The tail wheel/skid offers other advantages being small and lightweight, of relatively simple design, and causing lower drag in flight than a fixed nose gear, but in terms of handling qualities the disadvantages of the 'conventional' landing gear predominate, and they include inter alia:

- Poor forward field of view which can hide potential obstacles from the pilot when taxiing and obscures the runway during the early part of take-off roll, and the approach, flare to touchdown and landing roll.
- An absence of inherent dynamic directional stability – meaning that it has no natural tendency to align itself with the ground path of the aircraft but instead diverges – in the same way a single axle trailer behaves when being reversed.
- Mainwheel first contact at touchdown can cause a nose up pitch (which is largely prevented if a three-point landing is made), which increases the angle of attack and the lift thereby increasing the likelihood of bounce.
- Depending on the design of the tail gear, challenging directional control on the ground in crosswind/tailwind conditions.

Since this study concerns aircraft with 'conventional' landing gear layouts these disadvantages will be further discussed from a handling qualities perspective.

E.2 Restricted field of view

It may seem that field of view has no direct connection with aircraft handling qualities and this supposition is correct in terms of open loop stability and control, but when a pilot is closing an error loop his bandwidth may be lowered in the absence of adequate error queuing. It may take the pilot longer to notice an error and so the pilot's correction introduces a lag which may drive the system into instability in the form of a pilot induced oscillation.

A designer set the centre of gravity within limits and in small with a single engine mounted in the nose the pilot/crew mass is located to 'balance' that of the engine so that fuel and payload can be located around the centre of gravity. On conventional aircraft this often results in the pilot's station being significantly further aft than that found on an aircraft with a nose wheel. This rearwards location abetted by the arrangement of the engine and its ancillaries often block the pilots forward view and the tail down attitude further aggravates the problem.

The inability to see in directions one wants to see in can lead to anxiety which can lead a pilot to use an inappropriate technique. Perhaps using an overly nose-low attitude thereby causing the propeller to make contact with ground during the take-off run or allowing the aircraft to touch down prematurely leading to a bounced landing.

E.3 Directional Instability [on the ground]

When in free flight directional or yaw stability is provided by the vertical stabiliser (or fin) while yaw control is provided by the rudder. Given adequate vertical tail volume an aircraft should always exhibit static directional stability which is often referred to as weathercock stability – i.e., the tendency for the aircraft to align itself with the relative wind without pilot action. This directional stability is dependent on dynamic pressure which is at its lowest during take-off and landing and here, when rolling with the weight being borne by the wheels, it can be overpowered by the instability inherent in the tailwheel layout. A loss of directional control on the ground is often referred to as a 'ground loop' in which, the more the aircraft diverges directionally the greater is the tendency for it to diverge further. This can result in

a tight turn through 90° to 270° and may cause the landing gear to fail and/or a wingtip to be damaged by contacting the ground, or worse. This tendency calls for considerable pilot compensation to prevent it occurring through adopting a high gain control strategy designed to limit any directional wandering caused by crosswind or propeller effects to below the critical angle at which the error becomes uncontrollably divergent. The greater the distance between the centre of gravity and the mainwheel axles the more prone the aircraft is to loss of directional control.

E.4 Reaction on mainwheel first contact

In most landings there will exist a (hopefully) small residual vertical velocity following the flare and hold off. Given that the centre of gravity lies behind the main wheel axles, at the point of touchdown this vertical velocity will cause the rear of the aircraft to drop thereby increasing the angle of attack. This sudden increase in angle of attack may increase the lift and coupled with the reaction from the mainwheel spring system, cause the aircraft to bounce significantly and potentially in a way likely to lead to a second heavy landing with potential for damaging the aircraft, or a loss of control in another axis. The greater the distance between the centre of gravity and the mainwheel axles the more prone the aircraft is to this effect.

This situation is customarily avoided by making a three-point landing (thereby preventing any pitching moment on touch down) or even a slightly tail first landing which provides a nose-down moment which de-rotates the aircraft onto the mainwheels and into the three-point attitude automatically. Carrying out a three-point landing requires considerable pilot compensation when compared to the usual landing technique used in an aircraft with tricycle gear.

However not all aircraft with 'conventional' landing gear can be landed in the three-point attitude. The structure of large bomber/transport types may not be robust enough to cater for a misjudged three-point landing if the pilot flared too high, subsequently stalling heavily onto the runway. Some other types have such deficient stalling qualities that it is not safe to place them in the three-point attitude when close to the ground, while with others the relative lengths of the main and tail

gear result in a ground angle significantly higher than the stalling angle. In these cases, an alternative technique is used often referred to as a 'wheel' landing. In this case the pilot intends to touch down on the mainwheels first but knows that the tendency to bounce must be managed by appropriately timed control inputs on the elevator. Such inputs which range from freezing the elevator to a perfectly timed forward input to reduce the angle of attack. The latter can carry additional risk of the propeller striking the ground if the input is overdone. Once again significant pilot compensation may be required to make a 'wheel' landing.

E.5 Types of tail landing gear and attendant implications

Tail landing gear fall into two main types namely a tail wheel, or a tail skid. Tailwheels may be free to castor left and right, or they may be steerable through a linkage to the rudder control system, either of the above may be provided with a locking device to fix them in the central position. Aircraft with a tailwheel must rely on wheel brakes for stopping after landing and often for assisting steering when taxiing. On the other hand, aircraft with a tail skid are very rarely equipped with wheel brakes - the dragging effect of the tailskid will slow and stop the aircraft (on a natural surface but not necessarily on a paved surface) with the engine idling.

This absence of wheel brakes may be because the aircraft concerned was designed and built in an era before wheel brakes on aircraft had been developed or, to economise on cost, complexity or weight. In such aircraft directional control on the ground cannot be assisted by differential wheel brakes and is achieved by a combination of the aerodynamic effect of the deflected rudder and the design of the tail skid. The effectiveness of the rudder is dependent on the airflow around it which varies with the wind speed and direction relative to the aircraft and on any additional flow from the propeller.

A tail skid may be designed to be either; free to castor, steerable by the pilot through an interlink to the rudder control system (either of these may be fitted with a centre lock) or, fixed central. A freely castoring tailwheel or tail skid makes little contribution to directional stability on the ground and so the ground loop tendency discussed above is not resisted. Steerable tailwheels and tailskids may offer more resistance to directional instability depending on the robustness of the

linkage with the pilot's rudder control circuit. To avoid the possibility of a damaged tailwheel/skid jamming the rudder control such linkages usually employ a spring or bungee connection and this limits the effectiveness as a 'straightener' since the 'spring' will likely be overpowered once a directional divergence begins. A lockable tailwheel or skid, and the simple fixed skid, offer the best resistance to directional divergence on the ground.

Lockable tailwheels are often found on WW2 US and German aircraft but rarely on British designs. Lockable tailskids are vanishingly rare while fixed skids appear on a few light aircraft in the 1920's and 1930's. Castoring tailskids are found on aircraft from the beginning of powered flight through the 1920s, steerable skids are found in aircraft from the beginning of WW1 through to the 1940s. The importance of the above discussion is that aircraft not equipped with differential wheel brakes to assist steering on the ground must be able to taxi on the aerodrome in any orientation of wind angle. Without a means to prevent weathercocking a directionally stable aircraft will always turn itself into wind and frustrate the pilot's attempt to maintain a given track.

To manage the various arrangements of tail landing gear requires understanding and considerable pilot compensation; in terms of maintaining directional control of the aircraft on the ground, particularly in crosswind and downwind orientations, the ground handling qualities of such aircraft can be very challenging.

Appendix F - Relevant aircraft types flown by the researcher¹³

PRE-WW1 (Biplanes)			
Aircraft	Year	Aircraft	Year
<i>Bristol Boxkite</i>	1910	<i>Roe Triplane</i>	1910
PRE-WW1 (Monoplanes)			
<i>Bleriot</i>	1909	<i>Blackburn</i>	1912
<i>Deperdussin</i>	1910		
WW1 Fighters (Biplanes)			
<i>Avro 504K</i>	1914	<i>Bristol F2b</i>	1917
Bristol Scout	1915	Albatross DV	1917
<i>Sopwith Pup</i>	1916	Royal Aircraft Factory BE2e	1916
<i>Sopwith Triplane</i>	1916	Sopwith Snipe	1918
Nieuport 17	1916	DeHavilland-9	1918
<i>Sopwith Camel</i>	1917	Luftverkehrsgesellschaft LVG CVI	1918
<i>Royal Aircraft Factory - SE5a</i>	1917		
WW1 Fighters (Monoplanes)			
<i>Bristol M1c</i>	1917		
LYMPNE TRIALS 1923-1924 (Biplanes)			
<i>Hawker Cygnet</i>	1924		
LYMPNE TRIALS 1923-1924 (Monoplanes)			
<i>DeHavilland 53</i>	1923	<i>English Electric Wren</i>	1923
<i>Aerial Navigation Engineering Company - 2</i>	1924		
1920s-1930s (Biplanes)			
Sopwith Dove	1919	DeHavilland-87b Hornet Moth	1931
<i>DeHavilland-51</i>	1925	Arrow Active	1932
<i>DeHavilland-60</i>	1925	Bucker Jungman	1933
<i>DeHavilland-60x</i>	1928	Stampe Vertongen SV4	1933
<i>Hawker Tomtit</i>	1928	<i>Hawker Hind</i>	1934
<i>Polikarpov Po2</i>	1928	Bucker Jungmeister	1935
<i>Parnall Elf</i>	1929	<i>Gloster Gladiator</i>	1935
<i>Avro Tutor</i>	1929	<i>Blackburn B2</i>	1936

¹³ Aircraft types analyzed in Section 3 are highlighted

<i>Southern Aircraft Limited Martlet</i>	1930	Focke Wulf-44 Stieglitz	1937
<i>DeHavilland-82a Tiger Moth</i>	1931		
1930s-1940s (Civilian Monoplanes)			
<i>Comper Swift</i>	1929	Percival Gull VI	1934
DeHavilland-80 Puss Moth	1929	Miles Falcon	1934
<i>Desoutter Mk 1</i>	1930	<i>Miles Magister</i>	1937
<i>Miles Speed Six</i>	1934	British Aircraft Manufacturing Company – B.A. Swallow	1937
<i>Percival. Mew Gull</i>	1934	Luscombe 8	1937
DeHavilland -71	1927	Chilton DW1	1937
<i>DeHavilland-88 Comet</i>	1934		
1930s-1940s (Military Monoplanes)			
<i>Westland Lysander</i>	1939	<i>Hawker Sea Hurricane</i>	1941
Percival Proctor	1939	<i>Supermarine Spitfire V</i>	1942
Bucker Bestman	1939	Ryan PT-22	1942
Ryan STA	1940	Fiesler Storch	1942
North American Harvard	1940	Supermarine Spitfire IX	1943
POST WW2 (Tail Landing Gear)			
Aeronca Champ	1945	<i>Piper Super Cub</i>	1949
Miles Gemini	1946	<i>Percival Provost</i>	1950
<i>Avro Anson C19</i>	1946	<i>DeHavilland (Canada) Chipmunk</i>	1952