

CRANFIELD UNIVERSITY

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INVESTIGATION INTO AERO-HYDRODYNAMIC SURFACES FOR
WING-IN-GROUND EFFECT VEHICLE DESIGN

Centre for Energy & Power
Centre for Aeronautics

Doctor of Philosophy

Supervisor: Professor Phil Hart
Associate Supervisor: Professor Kevin Garry
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degree of PhD

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ABSTRACT

This project focuses on developing the required knowledge and engineering data to be applied in the preliminary design of a Wing-in-Ground Effect vehicle.

Three concurrent work programmes are carried out, covering experimental testing of a novel hull design, computational analysis of three wing profiles operating in ground effect, and an experimental programme to validate an unusual profile using an unconventional technique.

This work is intended to produce a reliable database of 2D aerodynamic coefficients by establishing a robust methodology for numerical solution. A detailed range of heights above ground and angles of attack have been included, and the methodology can be easily applied to additional profiles in the future.

A model wing was constructed and towed near the bottom of a water tank to replicate the physics and flow patterns of a wing immersed in an incompressible fluid moving over static ground. The selected profile was included in the computational work and the results of the two methods were compared.

A hull model was designed and built, then towed at high speed to assess its potential performance in the take-off phase of WIG operation. As a radiussed-chined slender hull, it would also be suitable for waterborne operation at modest speed, leading to the possibility for a dual-purpose vehicle comfortable in air or water.

Finally, a parametric geometry tool was developed to explore the design space and assess feasibility of various configurations. Relationships between primary components have been derived to allow sizing and positioning with corresponding powering estimates, to generate WIG conceptual designs.

Keywords:

WIG; CFD; ICEM; tank testing; experiment; model; airfoil; wing; naval architecture

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LIST OF ABBREVIATIONS

AAMV	Aerodynamically Alleviated Marine Vehicle
ACH	Aerodynamic Centre with respect to variations in height
ACP	Aerodynamic Centre with respect to variations in pitch
AoA	Angle of Attack, $[deg]$
AR	Aspect Ratio = b^2 / S
b	Wing span, $[m]$
BOA	Beam Overall, maximum beam, $[m]$
BWB	Blended Wing-Body
c	Chord length, $[m]$
C_D , c_d	Coefficient of drag = $Drag / \frac{1}{2} \rho V^2 S$
C_f	Coefficient of friction
C_L , c_l	Coefficient of lift = $Lift / \frac{1}{2} \rho V^2 S$
C_M , c_m	Coefficient of pitching moment = $Moment / \frac{1}{2} \rho V^2 S c$
C_p	Pressure coefficient
CFD	Computational Fluid Dynamics
CG	Centre of Gravity (mass)
CP	Centre of Pressure
D	Drag, resistance, $[N]$
DAC	Dynamic Air Cushion
DHMTU	Department of Hydromechanics, Marine Technical University, St. Petersburg
EGE	Extreme Ground Effect

Fn_L	Froude Number, length based = $V/\sqrt{gL}$
Fn_V	Froude Number, volume based = $V/\sqrt{g\nabla^{1/3}}$
GE	Ground Effect
GEZ	Ground Effect Zone
h	Height above ground, $[m]$
$\bar{h}$	Height above ground, normalised to chord length = h/c
HPMV	High Performance Marine Vehicle
IGE	In Ground Effect
k	Turbulent kinetic energy, $[m^2/s^2]$
kt	Knot, 1 nautical mile per hour
L	Lift, $[N]$
LCB	Longitudinal Centre of Buoyancy, $[m]$
LCG	Longitudinal Centre of Gravity (mass), $[m]$
LE	Leading Edge
LOA	Length Overall, $[m]$
LWL	Length Waterline, $[m]$
Ma	Mach number
MAC	Mean Aerodynamic Chord, $[m]$
MTOW	Maximum Take-Off Weight, $[kg]$
OGE	Out of Ground Effect
PAR	Power Augmented Ram
RANS	Reynolds-Averaged Navier-Stokes
Re	Reynolds number

S	Surface area, wing planform area, $[m^2]$
SSM	Static Stability Margin
TE	Trailing Edge
u	Flow velocity parallel to wall, $[m/s]$
U	Local velocity, $[m/s]$
U_∞	Freestream velocity, $[m/s]$
V	Velocity, forward speed, $[m/s]$
∇	Volume, $[m^3]$, also del operator Nabla
WF	Weight Fraction
WIG	Wing In Ground Effect
y^+	Dimensionless wall distance
α	Angle of attack, $[deg]$
β	Deadrise angle, $[deg]$
ε	Turbulent dissipation rate, $[1/s]$
μ	Dynamic viscosity, $[Ns/m^2]$
μ_T	Dynamic turbulent viscosity, $[Ns/m^2]$
ν	Kinematic viscosity = ρ / μ , $[m^2/s]$
ρ	Fluid density, freestream fluid density $[kg/m^3]$
ρ_∞	Freestream fluid density, $[kg/m^3]$
τ_w	Shear stress at wall, $[N/m^2]$
ω	Turbulence dissipation frequency, $[1/s]$

1 Literature Review

1.1 Introduction

Ground effect is a natural phenomenon that can be observed by witnessing large birds skim over the surface of the sea or watching aircraft float along a runway waiting to touch down. The first heavier-than-air flight likely never left the Ground Effect Zone (GEZ) and a few specialised craft since then have been designed specifically to operate entirely within this zone. This section will introduce some fundamental principles and concepts involved with operating a craft In Ground Effect (IGE).

Before beginning however, it is interesting to note that even during the extraordinary technological advances across all fields of engineering throughout the 20th century, particularly relevant being aeronautics, naval architecture, materials science, computer science and computational methods, etc., the realm of ground effect vehicles remains sparsely populated. Furthermore, the theoretical framework and indicative roadmap for exploratory research and development of this field remains scant, if it exists at all.

This project was created for that reason. If one wishes to design such a vehicle, there is currently no specific place to start. Embodying the adage ‘neither fish nor fowl’, to conceive the fish that swims yet also flies clear of its element without relying on surface support or submerged appendages, or the fowl that takes to the air but does not rapidly move free of the surface with all its inherent danger, the engineer that attempts to create such an object must straddle the aero-marine interface as deftly as the craft.

To that end, fundamental research into the hydrodynamic and aerodynamic concepts governing this field was conducted with the intention of understanding the physical requirements for successful implementation, thereby allowing some type of methodology to then be developed for design and analysis.

1.1.1 Basic Principles

It has been documented for approximately a century that an aerodynamic lifting surface in close proximity to a ground plane theoretically offers more efficient flight than is possible in free flight conditions (Wieselsberger, 1922). This efficiency comes in the form of increased lift for a given angle of attack and decreased induced drag. This effect was initially discovered empirically by pilots, then determined theoretically by mathematicians, and has been measured experimentally across a range of heights and wing aspect ratios for some limited cases.

By reducing the clearance of the entrained fluid in circulation around the airfoil, the squashed 'air cushion' results in an over-pressure on the lower surface, hence increasing the pressure differential and resultant force between the upper and lower surfaces. This can occur in two planes: when referring to a transverse section this is known as span-dominated and a longitudinal section is known as chord-dominated.

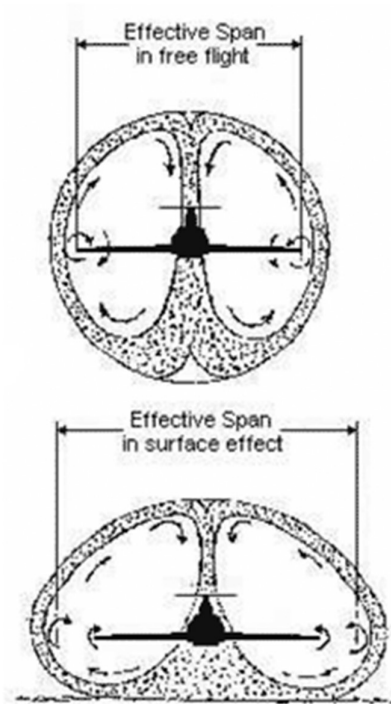


Figure 1-1 Spanwise circulation illustrating the squashed air cushion

Span-dominated ground effect. Aerodynamic drag is typically split into components of friction drag and lift induced drag. Although friction drag is a function of the wetted surface area of a vehicle, induced drag is a function of the geometry of lifting surfaces. The high-pressure lower surface meets the low-pressure upper surface at the wingtip, where a vortex is formed as the fluid flows from high to low pressure regions. The energy required to form these vortices is no longer available to the vehicle and is therefore known as lift induced drag.

The amount of induced drag is dependent on the spanwise lift distribution and aspect ratio of the wing. Aspect Ratio (AR) is defined as the relationship between the overall wing span and the Mean Aerodynamic Chord (MAC) and can be shown to be equivalent to span squared over total wing area. For a given amount of lift, a high AR wing typically has lower induced drag than a low AR wing, although devices such as wingtip fences can be used to reduce spanwise flow and thus increase efficiency of a low AR geometry. Interestingly, as a wing approaches the ground, efficiencies of high AR ratio and penalties of low AR are reduced as the effective span increases (see Figure 1-1) and it is common for Wing-in-Ground effect (WIG) craft to utilise very low span wing geometries.

Chord-dominated ground effect. Lift is the resultant force generated by differential pressure on the upper and lower surfaces of a wing. As a ground plane is approached, the magnitude of the high pressure on the lower surface is increased due to flow restriction caused by frictional resistance of the fluid molecules. This over-pressure is sometimes referred to as ram pressure, or as a captured air cushion, and has the effect of increasing the net lifting force. This additional lift is generally experienced at altitudes within one mean chord length and increases in magnitude as ground clearance is reduced. Figure 1-2 shows a simplified force diagram of a wing in freestream flight and the expected change in resultant lift force and location near the ground plane.

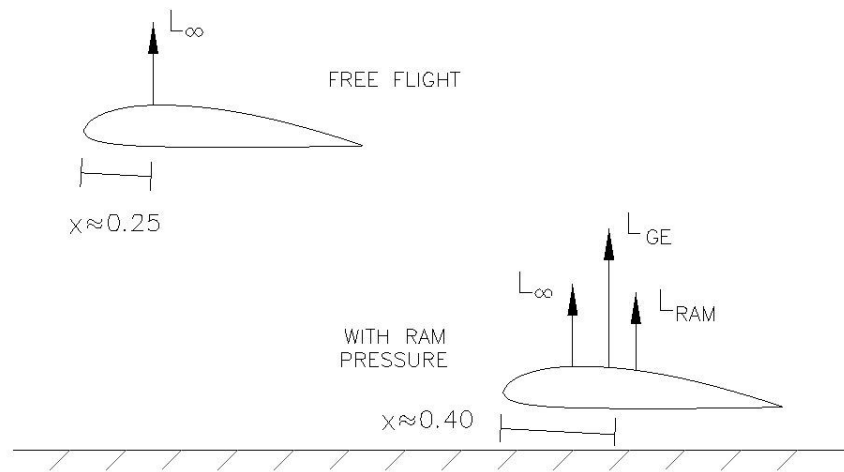


Figure 1-2 Simplified force diagram showing effect of ram pressure on a wing as compared to freestream flight

WIG craft aim to exploit this enhanced lift and reduced drag, having the potential to be more efficient than an equivalent aircraft configuration flying Out of Ground Effect (OGE) and at speed much greater than high speed marine vehicles. However, WIG craft designed to date have not been able to fully exploit this theoretical advantage, with reduced efficiencies often due to the inclusion of additional lifting and/or control surfaces and other required design compromises (Halloran and O'Meara, 1999).

1.1.2 Comparison to Aircraft & Marine Vehicles

The primary advantage of WIG craft versus other forms of marine vehicles is that of sustainable cruising speed. The pursuit of speed on or over water has led to the development of planing craft, multihulls, air cushion vehicles, surface effect craft, hydrofoils, and other advanced craft. Designing mechanisms for marine vehicles to generate lift (static or dynamic) can offset some portion of its weight and lower its effective displacement and wetted surface area, with a corresponding reduction in the hydrodynamic resistance. However, due to limiting factors such as safety, economy and comfort, a physical maximum speed attainable for passenger-carrying waterborne craft may exist around 75 kt; to exceed this would require designers to consider the

aerodynamics of the structures and utilise the significant aerodynamic lift available to create a hybrid hydrodynamic and WIG machine (Gee, 1999).

The concept of a sustention triangle has been proposed (see Figure 1-3), primarily by American naval architects, to categorise the forces involved in hydrostatic and hydrodynamic support of various types of High Performance Marine Vehicles (HPMV), and the contribution each type relies upon for its operation (McKesson 2002; Clark et al. 2004). McKesson (2002) has suggested extending this design space to a ‘sustention cube’ to offer broader applicability to very high speed HPMV and novel craft. The main difference between the two approaches is in the representation of aerodynamically supported vessels in a separate region to that occupied by hydrodynamically supported vessels. Each of these technologies can achieve much higher speeds than conventional displacement craft but all have their unique drawbacks and disadvantages, summarised as follows.

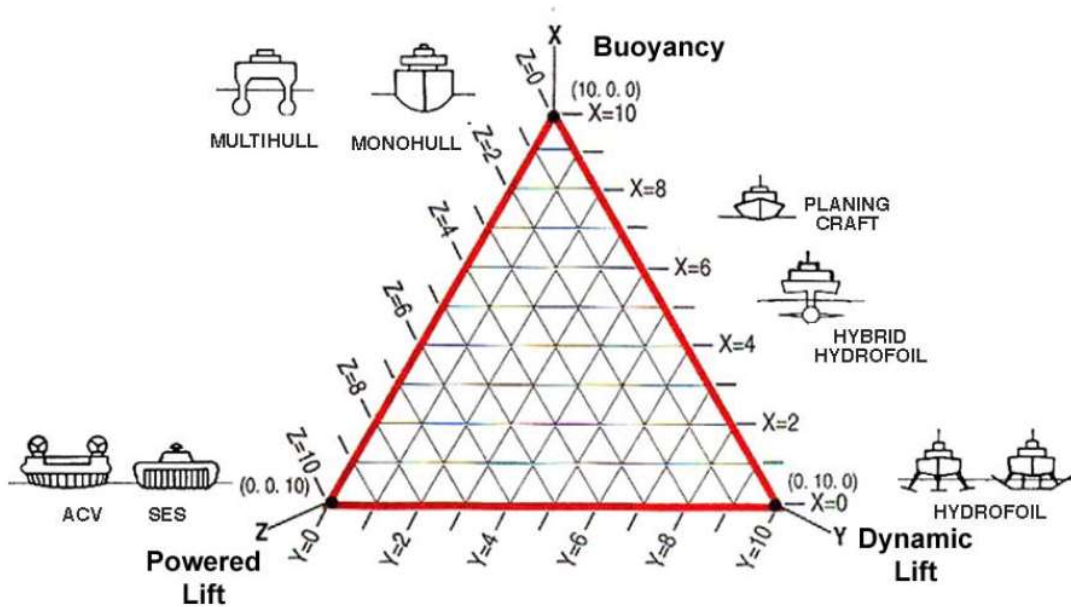


Figure 1-3 The sustention triangle for marine craft (from Clark et al, 2004)

Planing craft. As the self-induced bow wave limitation of displacement craft was studied and understood, initial attempts to overcome the so-called hump speed utilised single-hulled craft with flattish bottoms and a hard chine at the turn of the bilge. The purpose of this flat bottom was to deflect oncoming water downwards, thus generating hydrodynamic pressure loading that lifts the craft upwards due to Newton's third law of motion. Savitsky (1964) published an empirical design guide based on his work with seaplanes and planing craft have been a viable option for HPMV ever since. Record-breaking transatlantic runs have been realised using a planing hull (*viz.* Destriero in 1992) and nowadays their performance and powering characteristics are well-known. In addition to their high power requirements, wave-induced vertical accelerations and slamming events place high loads on the vessel structure and crew leading to structural failures, requiring increased scantlings and structural weights, injuries to personnel and fatigue to operators and passengers. Increasing the deadrise angle reduces these slam-induced pressures, although at the cost of reduced hydrodynamic efficiency.

Multihulls. The relationship between waterline length and total displacement of a vessel is typically one of the first parameters to be increased when higher speeds are desired. Long and slender hullforms create less wave-making, which generally constitutes the largest component of high-speed resistance. For a single hull, transverse stability is a function of the lateral movement of the centre of buoyancy, so a given hull must maintain sufficient beam to ensure adequate righting arms throughout a range of heeling angles. In order to overcome this minimum allowable beam, catamarans (and multihulls in general) structurally connect two or more hulls to provide high initial stability and wide cross-deck areas. The hulls can then become much narrower until other considerations like machinery requirements, tankage or internal hull volumes necessitate a new minimum girth.

Air Cushion Vehicle (ACV). Craft wholly or partially supported above the surface by a continuously self-generated pressurised air cushion. This captive air cushion reduces resistance as the vehicle rises from the surface, and also provides a suspension system to traverse uneven terrain or sea conditions. Amphibious ACVs are generally known as hovercraft, due to their ability to generate zero-speed aerostatic lift, and use a flexible skirt to maintain cushion pressure in a plenum chamber beneath the craft structure.

Water-only ACVs may use longitudinal sidewalls for a more effective seal, although at the cost of higher viscous and wavemaking resistance. These craft appear almost to be a mix of catamaran and hovercraft and are known as Surface Effect Ships (SES). The main drawbacks of the ACV include the power requirement for generating the air cushion and the sealing mechanism to maintain the over-pressure. Low pressures are desirable (typical range of 1.5 to 3.5 kPa) so suit low density payloads, e.g. passenger and car ferries, as high pressures lead to significant difficulties in flexible skirt engineering. Maintaining the seal and minimising wear and erosion of the skirt are ever-present issues facing ACV operation (Trillo, 1971).

Hydroplanes. Some of the highest speeds ever recorded on the water surface have been achieved by hydroplanes (≤ 140 kt, 72 m/s), small and lightweight weight craft characterised by two sponsons forward and a single propeller aft. These craft are designed so that operational running trim is realised just touching the after end of the sponsons and ideally a single blade of the surface-piercing propeller. There is typically a rear fixed wing that can be adjusted for prevailing conditions and a forward control surface, or canard, which the driver can change the angle of attack and subsequent amount of lift via a foot pedal. Racing classes install a single Lycoming T55 turboshaft engine connected to a single speed, direct drive gearbox to achieve extremely high power-to-weight ratios (H1 Unlimited, 2017). However, due to their diminutive size and inherent pitch instability these vehicles cannot be scaled to function effectively as larger craft.

Hydrofoils. Placement of a flat, curved or profiled plate under the water surface transverse to the direction of travel allows a relatively small area to produce significant amounts of lift. However, as the foil rises from deeply submerged to near-surface the generation of lift for a given angle of attack decreases. The lift-curve slope does not appear to vary considerably but the angle of zero lift increases, resulting in an offset of the lift curve. Furthermore, induced drag for a given lift coefficient also increases (Wadlin, Shuford and McGehee, 1955). Additionally, high speed operation of a conventional hydrofoil is generally limited by the occurrence of cavitation on the upper surface of the foil, with a resulting increase in drag and break down of lift (Curry, 1948). Cavitation is the formation of water vapour on the low-pressure surface due to negative dynamic pressures exceeding the fluid vapour pressure. The vapour bubbles then collapse

as the pressure gradient increases, typically resulting in erosion of the surface as well as loss of performance. It is usually desirable for stable operation either to suppress the cavity formation entirely or to design the hydrofoil to have acceptable characteristics in the cavitating condition (Waid and Lindberg, 1957).

Aerodynamically Alleviated Marine Vehicle (AAMV). The term “aerodynamic alleviation” appears to have originated with the Ekranocat concept by Doctors (1997) who suggested a catamaran with a streamlined, wing-like lifting superstructure and additional defining features of reduced hydrodynamic frictional resistance and optimised wave interaction patterns between the demi-hulls. Surface-piercing propellers were proposed for primary propulsion. This may be considered a developmental category as not many craft of this type have been built.

As speeds increase, the addition of an aerodynamic lift component can be expected to improve the overall lift-drag ratio. However, the location and magnitude of this component must be carefully considered. Matveev (2012) suggested that progress in the field of aerodynamically supported vessels was hampered by a lack of dynamic mathematical models, and so presented a framework to analyse unsteady longitudinal motions for a vessel supported by aerodynamic and hydrodynamic lift as well as a vertical component of propeller thrust. Collu (2008) presented a thesis of unified equations of equilibrium and equations of motion to predict the dynamic performance of AAMV configurations.

This concept has been proven to function successfully with a recent prototype constructed and sea-trialled, of approximate length 10.1 m, carrying 12 passengers at speeds up to 50 kt. Hydrodynamic lift is generated by a stepped planing hullform but unfortunately no test data or numerical prediction showing the contribution of the aerodynamically shaped superstructure has been found in the public domain.

Seaplanes. An entire class of fixed-wing aircraft known as seaplanes, which will be defined to include floatplanes and flying boats, evolved and thrived with the need to travel and land in austere ports. In common with marine craft, seaplanes eliminate the requirement to build runways or extensive infrastructure by utilising the water surface to provide a flat surface (when calm) with few obstructions for take-off runs (Stout, 1953). Historically, this proved to be a major advantage, allowing travel to undeveloped

locations at speeds typical of general aviation aircraft. However, in addition to the inherent burden of aircraft certification, operation and maintenance, seaplanes are generally the least efficient form of fixed-wing aircraft due to the structural, hydrostatic and hydrodynamic demands of the floats. Empty weight fractions, i.e. the ratio of the empty weight of the vehicle (structure, engines, landing gear, avionics, etc.) to the all-up take-off weight, are the poorest of all fixed-wing aircraft types (Raymer, 2006).

Helicopters. Although not directly comparable with the types of vehicles included here, helicopters and rotary-wing aircraft are nevertheless utilised for shorter length, high speed passages, typically where short or vertical take-off is required. A major advantage of rotary-wing aircraft is their ability to hover, although at the expense of complex flight controls and constant control inputs and corrections to maintain position.

Cost of helicopter ownership and operation is very high and the mechanical systems are complex and expensive to maintain. Specialised heavy-lift helicopters are available, the largest being the Russian Mil Mi-26 that has a payload capacity of approximately 20 000 kg, although the Bell UH-1 is more representative of the majority of general purpose helicopters with a payload around 1760 kg. Bristow Group, the largest provider of helicopter transportation services to the offshore oil and gas industry, operates around 600 helicopters to generate >60% of their global revenue (Bristow, 2013) with Call When Needed (CWN) contracts awarded with hourly rates in thousands of US Dollars per hour.

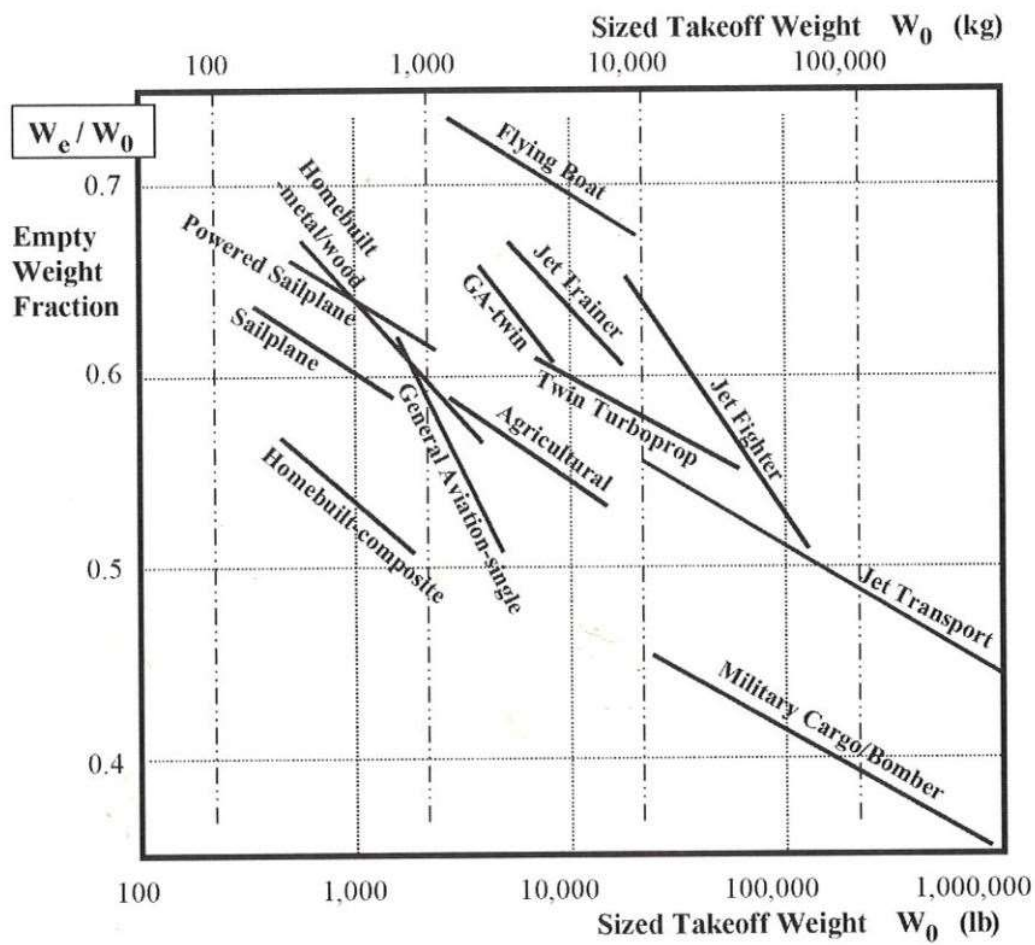


Figure 1-4 Typical empty weight fractions for various aircraft types (from Raymer 2006)

1.1.3 Transport Efficiency

Marine vehicles have maintained a permanent place in the global economy for several reasons, such as their capability to transport a high volume of goods over large distances efficiently, and their effectiveness in smaller and more localised routes and applications. Aircraft have been able to deliver lighter and smaller cargoes across large distances faster than ships but with increased cost and fuel required per unit mass of vehicle and cargo.

The concept of transport efficiency has been developed as a derived metric to compare various modes of transportation in terms of the power required, and therefore fuel burned, to move a payload at a given speed.

Gabrielli and von Karman (1950) first identified the inverse relationship whereby efficiencies for various types of vehicles over land, sea and air generally decreased as their speed regime increased. A specific tractive force, ε , was simply defined as:

$$\varepsilon = \frac{P}{W V} \quad (1-1)$$

where P = power required [kW], W = weight, mg [kN], V = speed [m/s]

When typical values of specific tractive force for various vehicle types were plotted versus absolute speed, distinct groupings became apparent. Furthermore, the resulting trend line encompassing all vehicles marked a Pareto front, or a technical limitation that was not able to be overcome at that time.

Yong et al. (2005) updated the study initially conducted by Gabrielli and von Karman, showing the relative speed and transport efficiency of current modes of transportation approximately 50 years further on (see Figure 1-5). Whilst some progress has been made in achieving higher speeds for a corresponding specific tractive force, a gap still appears between high speed, low efficiency modes (e.g. Concorde or supersonic aircraft) and low speed, high efficiency modes (e.g. super tankers and freight trains). This gap is shown as the highlighted region. There is an opportunity for WIG craft to occupy this gap by combining speeds typical of light fixed-wing aircraft and helicopters, with the installed power and related fuel burn typical of high-speed marine vessels for a given payload.

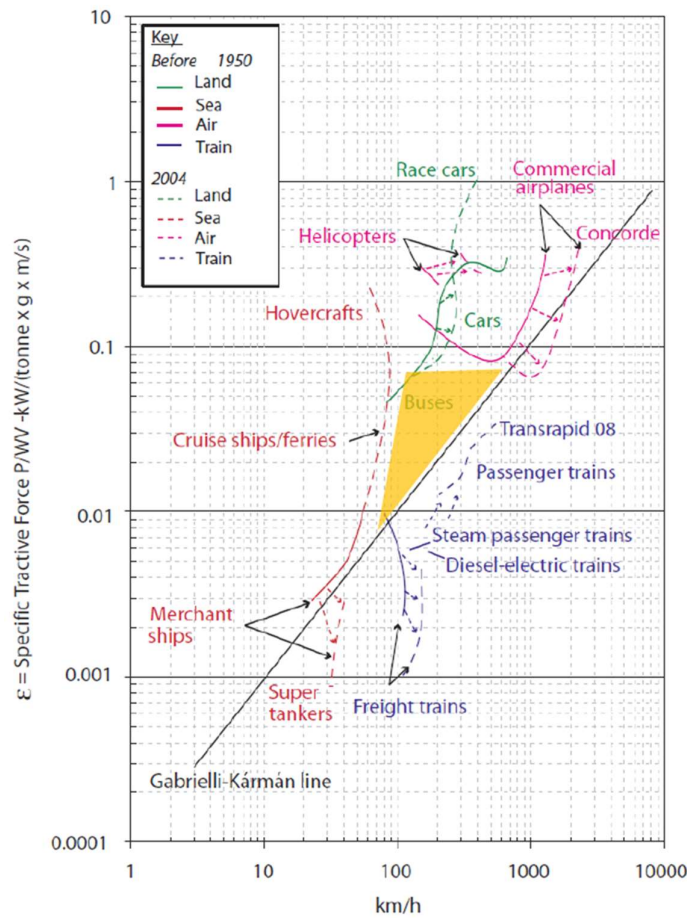


Figure 1-5 Gabrielli – von Karman diagram of speed vs power required to demonstrate transport efficiencies of various modes of transportation

The resulting increase in transport efficiency utilising WIG craft may allow the movement of people and cargo over water with much greater comfort, speed and efficiency than is currently achievable by other methods.

Similar concepts have been developed specifically for marine craft to link parametric relationships between specifications such as speed, range and payload, with the resulting design characteristics of installed power, lightship weight and fuel required. The Transport Factor (TF) was first documented by Kennell (1998) for a variety of ship types including conventional and unconventional hull designs. Overall TF for a given vessel was presented as the sum of the components of ship, cargo and fuel weight groups.

Almeter (2008) then focussed on TF for smaller HPMV of $F_{nV} \leq 10$ to address common errors in performance predictions, whereby general categories such as underestimated vessel displacement, overly optimistic powering and propulsor efficiencies were highlighted. Trends of technical and physical limitations for various types of HPMV were presented, as shown in Figure 1-6. Note that TF appears as a reciprocal relationship to that of specific tractive force, as a greater TF for a given speed indicates a more efficient vessel. Volumetric Froude Number is as defined in equation (1-2).

WIG has the potential to improve on currently achievable TF values as power requirements are significantly reduced during very high-speed operation, effected through the reduction of total vehicle drag by eliminating the component of hydrodynamic resistance.

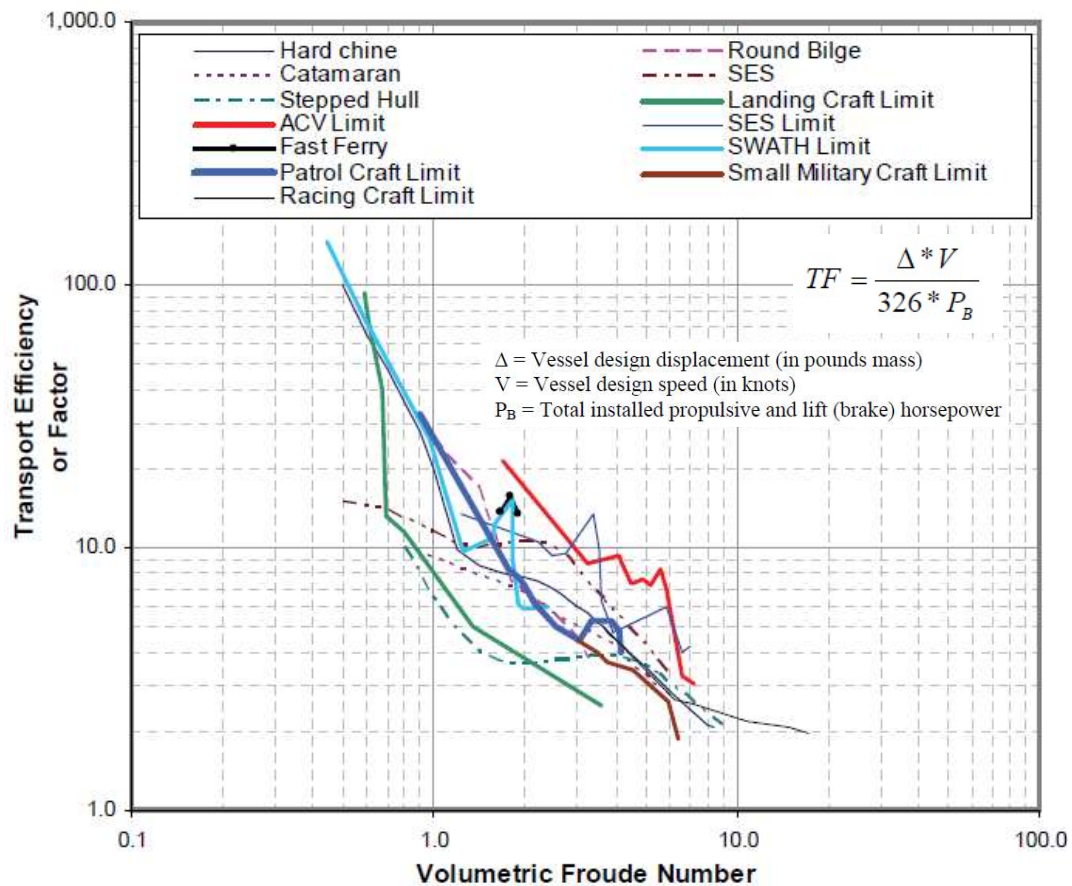


Figure 1-6 Summarised transport efficiency data for HPMV (from Almeter, 2008)

Although WIG craft are not covered under existing codes and regulations for HPMV, they are nevertheless recognised by the International Maritime Organisation (IMO) as marine vehicles, perhaps mainly due to their operation alongside other waterborne craft and utilisation of the same collision avoidance rules as conventional shipping. For craft carrying 12 passengers or more there are three type designations of classification based on aerodynamic capabilities:

- A. Craft certified for operation only in ground effect;
- B. Craft certified to temporarily increase altitude to a limited height outside the influence of ground effect but not exceeding 150 m (490 ft) above the surface;
- C. Craft certified for operation outside ground effect and exceeding 150 m (490 ft) above the surface.

Type C are defined as aircraft by the International Civil Aviation Organization (ICAO) and should comply with all relevant ICAO requirements; IMO guidelines do not apply.

However, the regulatory framework for Type A and B permits these craft to be designed, constructed, operated and maintained in accordance solely with maritime regulations (IMO, 2002), thereby avoiding the potentially prohibitive financial cost associated with engineering design approval through civil aviation authorities.

1.1.4 Brief Overview of Notable WIG Craft

The first recorded vehicles specifically designed for the exploitation of Ground Effect (GE) were produced by Toivo Kaario in Finland, most notably an “Aerosledge” built in 1935 for high speed travel over ice, with low aspect ratio main wing, single forward mounted propeller directly ahead of the wing, dual horizontal stabilizers extended far aft, with two narrow skis for ground contact (Rozhdestvensky, 2006).

Numerous GE studies were conducted by the US Department of Defense and scientific research organisations during the decades of 1950-60s, although the focus of the majority of configurations included discus-shaped geometries and annular jets (Frost & Moody 1956; Kuhn et al. 1960; Earl 1962). The general conclusion was that GE machines had only limited application in their areas of interest, *viz.* heavy lift of high-priority cargo over

an uneven surface. On the basis of predicted performance, the increase in mobility and operating speed could only be accomplished with large vehicles having very high rates of fuel consumption (McHugh and Jochums, 1963).

However, it was around this time that systematic WIG craft research and development began in a very different location, led by chief designer Rostislav Alexeyev of the Central Hydrofoil Design Bureau (CHDB) in Nizhniy Novgorod, USSR. During an ambitious and well-funded program under the Soviet Navy, a series of prototypes and testing of various configurations led to the largest airborne vehicle of its era, the KM, popularly known in the west as the Caspian Sea Monster (see Figure 1-7). The archetypal Alexeyev design features that characterise these vessels include a midship-mounted, low AR, rectangular straight main wing; large tail mounted horizontal stabiliser with substantial dihedral; well-defined long and slender fuselage; and forward mounted engine thrusters, typically having the exhaust gasses directed under the wing as a means of increasing lift forces at lower speeds (Komissarov and Gordon, 2010).

Approximately a decade after the Soviet programme began, smaller scale WIG development was funded by the West German Ministry of Defence, which awarded contracts for several designs to Alexander Lippisch, pioneer of the delta wing planform that found use predominantly on supersonic jet aircraft. The initial prototype denoted X-113 single-seat test craft was built in 1970 by Rhein Flugzeugbau GmbH (RFB) and following on from its success, the similar but larger six-seat X-114 was completed in 1977, as a prototype vehicle that would be suitable for coastal patrol duties. These craft shared a configuration comprising a fuselage with stepped planing lower surfaces, reverse delta main wing with significant anhedral and tapered chord, small tail surfaces, mounting a single propeller above the fuselage in a pusher configuration, and planing floats extending forward from the main wing tips. Noteworthy is the much smaller size compared to the Alexeyev designs where the Maximum Take-off Weight (MTOW) of the largest was 1500 kg compared to 544 000 kg for the Soviet KM (Yun, Bliault and Doo, 2010).



Figure 1-7 The archetypal Soviet WIG, the KM pictured here with white 04 tail marking



Figure 1-8 The second Lippisch WIG, the X-114 flying in 1977

Although there have been smaller WIG craft scattered throughout the world, predominantly in Russia, China and south-east Asia, very few have achieved the milestone of commercial viability. The most promising to date have been the descendants of the Lippisch vessels, most likely due to a combination of relatively stable and safe operation, prototype availability, and smaller overall size that requires lower capital expenditure to design and construct, and lower operational expenditure including crew training expense.

Significantly, the Singaporean company WigetWorks Pte Ltd was established for the main purpose of commercialising WIG technology in 2004. After purchasing patents, intellectual property rights and a working prototype from an Australian company called FlightShip, they now operate the M/V AirFish 8-001, certified for up to eight passengers. The craft was officially registered as a commercial vessel in the Singapore Register of Ships in 2010 and classed by Lloyds Register with notation 100 A1 WIG MCH, Type A, Passenger, WTL 0.5/WEL2.0, WSC 25 (WigetWorks, 2010).

Recent American attempts at heavy lift WIG craft are not included here. The reasoning is twofold: primarily these are not identifiable ground effect machines, and none have ever been built. The Boeing Pelican design is a typical example, funded through military research grants, but is no more WIG craft than the Hughes H-4 Hercules seaplane, constructed in California during the post-war years.

1.2 Implementation

Preliminary research studies into WIG feasibility for military/defence roles as well as commercial viability have been undertaken by many nations over the past couple of decades, with similar conclusions: that a WIG vehicle is a credible option for many tactical and strategic missions, but that there are a few technical challenges that have yet to be demonstrably overcome, although there is no inherent impediment to this development, especially when considering modern technologies that could be applied to lightweight structures, automated flight controls, and efficient propulsion systems (ARPA, 1994; Halloran and O'Meara, 1999).

1.2.1 Speed, Wing Design & Powering

Similar to aircraft in free flight conditions, WIG wing design is closely linked to the desired speed range and the required Thrust-to-Weight ratio (T/W). A smaller wing generates less parasitic drag due to less wetted surface area, which becomes a greater component of overall vehicle drag at higher speeds due to the proportionality of resistance forces to speed squared. Clearly, to achieve higher speeds installed engine power and resultant thrust produced must be greater than if a lower speed range is acceptable for a given vehicle. Higher T/W would indicate faster accelerations and a shorter take-off distance, all else being equal.

Wing loading, defined as the total vehicle mass divided by reference wing area, is inherently linked to design lift coefficient at design speed, and not only impacts aerodynamic performance but also carries a knock-on effect through to the structural arrangement and mass of the wing. Lighter and slower craft, e.g. gliders and General Aviation (GA) aircraft, typically have lower wing loadings than faster and/or heavier aircraft such as military combat, transport or large commercial aircraft. Higher wing loading would indicate longer take-off distance at a higher speed, all else being equal.

WIG craft have been designed and constructed covering a wide range of speeds, wing loading strategies and size of installed power plant. A few general trends have been noted which will be summarised in the following subsections.

1.2.1.1 Soviet/Russian Programme and Design Concepts

As outlined in Section 1.1.4, the CHDB in the USSR was the responsible design authority for development of large scale WIG craft. As suggested in the name of the bureau, their work began designing vessels supported by hydrofoils in the pursuit of high-speed performance of marine craft. Although a range of successful hydrofoil craft were developed and put into operational service, the fundamental limitations of this type of craft could not be avoided: firstly, the inherent speed threshold imposed by vapour pressure of the operating fluid; and secondly, the ride height and heave/pitch control system.

In an effort to overcome the operational speed restriction and self-stabilise the lifting surfaces, aerodynamically generated forces were used to sustain the vehicle. These craft were known as *ekranoplan*, or “screen” (surface) plane. Research into suitable aerodynamic layouts led to the first prototype of tandem wing configuration in 1961. The SM-1 utilised a rectangular wing forward with full-length flap and trapezoidal wing aft, fitted with an elevator on the trailing edge. The aft wing was mounted at the stern. The longitudinal stagger between the wings normalised to main wing chord length was approximately 2.5, leading edge to leading edge. Vertically, the gap was very small with the aft wing higher, indicating slightly negative stagger (see Figure 1-9). This prototype proved the fundamental concept of close GE flight and resulted in satisfactory stability and controllability characteristics but also what was considered excessively high take-off and landing speeds (Komissarov, 2002).

In general, optimised tandem arrangements may have several advantages over a conventional main wing and tail system: firstly, the lift vector of both wings is upwards; second, the longitudinal separation between the wings results in a vehicle that is less sensitive to changes in centre of gravity (mass) and is more stable in flight (Korolyov, 1998); and third, the tandem wings can be positioned to induce beneficial interactions in the aerodynamic circulation that can result in reduced drag compared to two individual wings in isolation, as described by general biplane theory (Munk, 1923). In this particular case, due to the high degree of separation between the wings, it appears that the intent was to reduce interactions to a minimum, presumably as the influence of GE on biplane theory was unknown.

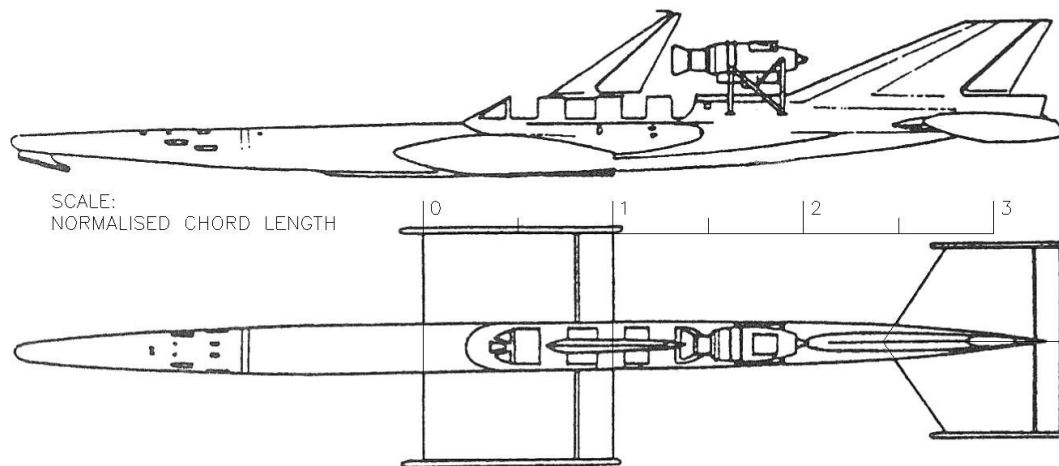


Figure 1-9 Diagram of Soviet SM-1 prototype detailing wing configuration

To improve take-off characteristics, the following prototype, SM-2, was fitted with the engine in the forward part of the fuselage instead of above and behind the cockpit, arranged so the efflux would be directed under the main wing. The configuration of this craft was a more conventional aircraft layout with a single main wing and T-tail assembly with high-mounted horizontal stabiliser and elevator control. The leading edge of the wing was initially swept back but later in the testing programme was changed to a straight leading edge, resulting in a rectangular planform, as this improved the effect of the under-wing blowing. Additionally, the thrust produced by a single forward engine with bifurcated nozzles was inadequate for cruise conditions and an additional engine mounted at the base of the tail was added. Maximum speed with the dual engine arrangement was 145 kt (75 m/s).

This prototype was built and tested in 1962; after the modifications were made the designation was changed to SM-2P, and the resulting layout would prove to be the archetype for all of the following major craft produced for the Soviet Navy.

The series of prototypes continued with eight SM designated craft constructed but later models were either refinements or minor modifications to the general configuration, instrumented testbeds for detailed measurements of performance characteristics, or 1:4 scale models of larger parent craft to be built (Komissarov, 2002).

To quantify the operational speed range, the marine concept of Froude number will be used, with reference to the displaced volume when floating hydrostatically. This metric allows a dimensionless speed comparison of various types of high-speed craft even when their size or form is quite different. The definition of volumetric Froude number is given as:

$$Fn_V = \frac{V}{\sqrt{g \nabla^{1/3}}} \quad (1-2)$$

where V = speed [m/s], g = gravity, [m/s²], ∇ = volume [m³]

Typical Fn_V values for the SM prototypes ranged from around 12 – 20, the range including cruise and maximum speeds. As shown in Table 1-1, although the measured speeds of the largest full-size craft were over three times greater than those of the smallest prototypes, the non-dimensionalised speed range was quite consistent across the entire Soviet programme.

The largest WIG ever constructed was designated KM (*Korabl Maket* or “ship model”), first tested in 1966. For approximately two decades this was the heaviest man-made machine to take flight. In 1988 the Soviet-built strategic heavy airlift cargo transport Antonov An-225 was flight tested with a reported MTOW of 640 t (Taylor and Munson, 1987). The KM required more than 1000 kN of thrust generated by ten non-afterburning Dobrynin VD-7 turbojet engines, configured as eight booster engines forward and two cruise engines mounted aft, to propel the craft at over 270 kt (139 m/s). This propulsion arrangement may appear excessive or inefficient, especially when considering that the forward engines were idling during cruise. However, when compared to much more modern aircraft of similar proportions and payload capacity (see Table 1-2), the KM achieved a lower T/W ratio (Airbus 2016; Scaled 2019).

The KM was not used in an operational role but later ekranoplans were developed for strategic and tactical missions such as carrying troops and military hardware, as a rapid-insertion missile platform, and later for search and rescue operations.

Orlyonok (Project 904) was a semi-production run of four vessels constructed for the Soviet navy during the years of 1975-1980. This craft incorporated a hinged nose section and integrated loading ramp to allow roll-on/roll-off loading of ground-based vehicles. Several variants were subsequently designed for diverse roles including anti-submarine warfare, civilian passenger transportation (denoted A-90.150), and Arctic prospecting over shallow water and ice (MAGE), although these craft were never built (Komissarov and Gordon, 2010).

Lun (Project 903) was launched in 1986 for the purpose of delivering six Moskit anti-ship cruise missiles. Ten vessels were initially planned over two fiscal periods but this was subsequently cut back and finally reduced to a single one. This vessel carried all of its engines forward on the pylons aft of the cockpit, primarily to keep the efflux from launching missiles away from the turbofan intakes. It is not known what impact this had on the overall propulsive efficiency.

Spasatel (Project 9037) was the 1992 conversion of a second *Orlyonok* that was started several years earlier but work had been stopped at around 80% completion. This was to be a demilitarised version, able to fulfil multiple search and rescue capabilities. Arriving on-scene to assist vessels in the event of sinking, fire, etc., could be achieved much quicker than conventional marine craft and *Spasatel* had sufficient internal volume for hospital accommodation for up to 80 patients, including dedicated facilities for nuclear radiation. A submersible was to be carried on the fuselage for submarine and subsea rescue operations. *Spasatel* was never fully completed.

These craft were all smaller than the KM but nevertheless each of the vessels that were completed and operational performed their intended missions very well. The development of this line of craft was far more successful than any other programme but was eventually halted due to political and economic reasons around the time of the collapse of the Soviet Union. The CHDB still continues work on WIG craft but of much smaller size.

Table 1-1 Performance characteristics of Soviet WIG craft

	Length m	Span m	MTOW kg	Vcr km/h	Fnv cr -	Vmax km/h	Fnv max -
SM-1	20.0	4.5	2830	170	12.73	270	20.22
SM-2P	20.0	5.25	3200	170	12.47	270	19.81
SM-3	14.5	3.8	3400	160	11.62	180	13.07
SM-4	20.0	7.5	4800	200	13.71	230	15.77
SM-5	18.0	9.5	7300	200	12.79	230	14.71
SM-6	31.0	14.8	26500	300	15.47	350	18.05
SM-2P7	19.4	9.4	6300	250	16.38	270	17.69
SM-8	24.5	9.5	8100	200	12.57	220	13.83
Orlyonok	58.1	31.5	140000	375	14.66	400	15.63
Lun	73.8	44.0	380000	450	14.89	550	18.20
Spasatel	73.8	44.0	390000	450	14.83	550	18.12
KM	92.4	37.8	544000	430	13.40	500	15.59

Table 1-2 Comparison of selected parameters for KM and modern aircraft

	MTOW		Thrust kN	T/W -	Cruise Speed km/h
	t	kN			
KM	544	5337	1030	0.193	450
AntonovAn-225	640	6278	1377	0.219	800
Airbus A380-800	575	5641	1360	0.241	900
SC Stratolaunch	590	5785	1514	0.262	~800

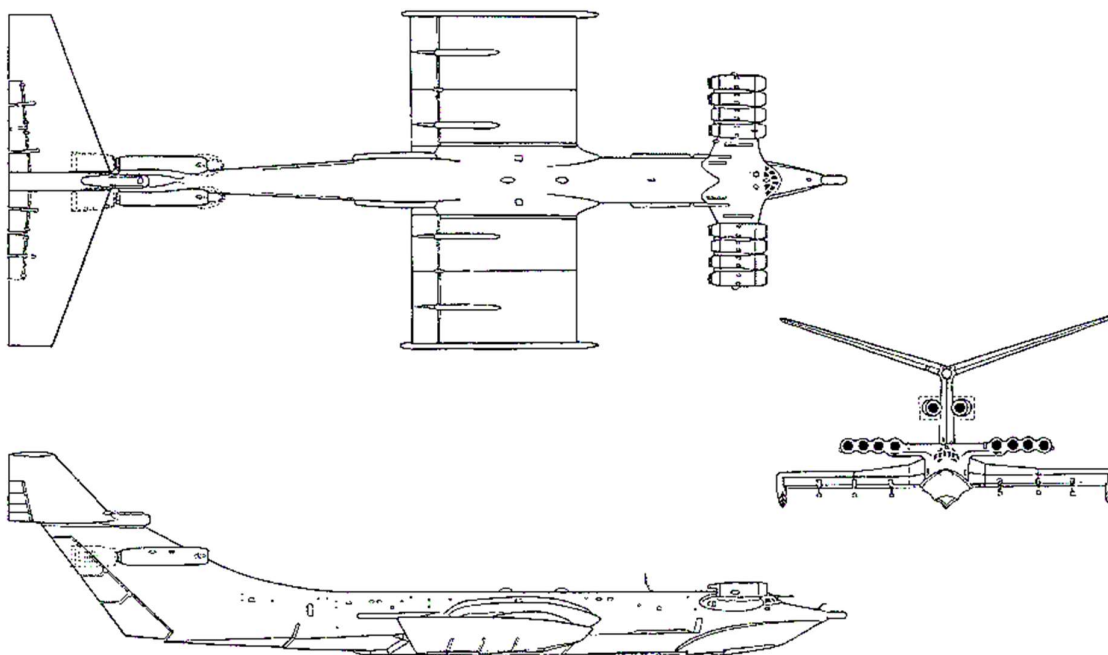


Figure 1-10 3-View diagram of the Soviet KM

1.2.1.2 German Development & Derivatives

As described in Section 1.1.4, the German craft were much smaller than their Soviet counterparts but were similar insofar as they also shared identifiable common design features. The single reverse delta wing configuration with high-mounted horizontal stabiliser was used for all of these craft. The highly tapered wing formed the characteristic triangular planform with straight or slightly swept forward leading edge. Spanwise, the wing was angled downwards towards the tips and the trailing edge practically enclosed the volume beneath the wing for maximum ram pressure or air cushion effect. Winglets positioned outboard of the main wing and angled approximately 30° from vertical housed ailerons for roll control.

Urquhart et al. (2006) later showed that the reverse delta planform with this anhedral angle and closed trailing edge exhibited only a small change in pitching moment as ground clearance was reduced and lift coefficient increased. The operation of the T-tail in the OGE zone was also confirmed, showing no influence of GE across the range of tested heights, so maintaining predictable control forces.

Hanno Fischer, a technical director of RFB during the X-113 and X-114 development, and partner Klaus Matjasic developed a derivative design called AirFish-3 (AirFish 1 and 2 were smaller prototypes), the rights of which were subsequently sold several times to companies of various nationalities. A slightly larger eight-seater design was eventually commissioned by an Australian company, called FlightShip-8 for intended use in a commuter ferry role (Yun and Bliault, 2012).

The FlightShip company encountered financial difficulties in 2002-03, and was subsequently purchased with the intent to complete development of the craft to commercial viability as a passenger ferry. The purchasing company, WigetWorks Pte Ltd, now operates what they call the M/V AirFish 8-001.

Although there are smaller WIG craft scattered throughout the world, built to various designs, very few have achieved the milestone of commercial viability. The most promising to date have been the descendants of the Lippisch vessels, most likely due to a combination of relatively stable and safe operation, prototype availability and smaller size that allows costs to remain manageable.

Table 1-3 Characteristics of Soviet and German WIG craft

Soviet	German
Low AR straight wing	Reverse delta wing
Zero sweep, no taper, dihedral	Forward sweep, significant taper, anhedral
High wing loading	Low wing loading
Large tail OGE required	Smaller tail area can be used
Allows use of flapped wing, with separate elevator at tail	Small movement of CP through mode transitions, less control required
Typically longer, slender vessel	Typically more compact vessel
High speed design, $V > 250$ km/h	Low speed design, $V < 150$ km/h

1.2.1.3 Selected Other Craft

In addition to the two primary developmental branches, there have been a number of hybrid craft that exhibit a mixture of design features, e.g. underwing-blowing on a small lightweight vehicle with low-mounted wing, or have incorporated design features that have not been widely pursued, e.g. tandem lifting surfaces. Some of these are summarised as follows.

Russian river craft. After military funding sources were no longer available, the ex-Soviet WIG designers quickly realised that smaller craft were likely to be more feasible to build and operate. As it was not possible to produce commercial WIG vehicles capable of free flight on a large scale, smaller and simpler DAC craft (see Section 1.2.2.2) became the focus, intended only for travel very close to the surface. A number of these designs began to come from the CHDB drawing boards suitable for river navigation, including concepts for single-seat, single-engine craft with unusual features such as inflatable pontoons.

The Volga-2 was the first of the commercially intended, smaller and slower DAC-type WIG built in 1986. Accommodation was provided for seven passengers and one pilot. There were no altitude controls as operation was limited to the Extreme Ground Effect (EGE) zone. Notably, the vessel was considered amphibious as the ram pressure created by the underwing blowing created a zero-speed static air cushion that allowed it to hover over sea or land at low speeds.

A successful vessel known as Amphistar was certified for passenger service in 1997, designed and produced by personnel from the CHDB. This craft was IMO Type A certified and is an archetypal small DAC WIG (Sinitsyn, 1996).

Chinese & Asian variants. Many of the WIG craft manufactured or otherwise produced in China and south-east Asia in general are small vessels that are very similar to the Russian river craft. There is typically a low rectangular wing with end plates, short fuselage, high T-tail and two forward-mounted propellers. Many of these craft have come from the China Shipbuilding Scientific Research Centre (CSSRC) and Marine Design and Research Institute of China (MARIC). A small WIG known as Swan is typical of this DAC type.

Tandem wing flairboat. After the first Soviet prototype, SM-1, the tandem configuration was not pursued further by CHDB and its appearance in WIG craft has been scarce. As stated previously, a tandem arrangement can offer several advantages over a main wing and large tail. Jorg (1997) presented a concept for a true tandem arrangement with two rectangular wings of equal planform dimensions with parallel leading and trailing edges, connected by wing tip fences. Remote controlled models test had shown that the Lippisch reverse delta configuration was hard to steer and reacted poorly to disturbances during flight, and this tandem proved to be more longitudinally stable during cruise with improved manoeuvrability.

The Soviet tests also found the stability characteristics were satisfactory but the required take-off speed was deemed to be too high for their speed range, up to 145 kt. For a similarly sized craft, the flairboat mass is reported to be 1500 kg for six passenger capacity, although with a maximum speed around 80 kt (41 m/s), similar to the Lippisch designs. At this speed range the stability advantages of the tandem may outweigh the shortcomings that were found when pushed to almost twice the speed.

1.2.2 Technical Impediments

Although GE technology has been shown to function effectively in variety of craft configurations, technical challenges still remain that need to be overcome before commercial service could become routine. The challenges for any emerging vehicle technology are to show that it should be considered fundamentally safe and that a clearly defined advantage can be shown over existing methods. Correspondingly, two of the greatest challenges for WIG development revolve around demonstrating sufficient static margin to ensure longitudinal stability and reducing unnecessary power and fuel consumption by efficiently lifting off from the water surface.

1.2.2.1 Longitudinal Stability & Control

One of the main technical problems in the development and commercialisation of effective WIG is ensuring motion stability and good seaworthiness. Frequent crashes of WIG craft and high speed air-assisted boats demonstrate the importance of this issue (Kornev and Matveev, 2003).

The fundamental causes of the majority of these accidents are control problems or structural failures due to insufficient strength for the loading experienced. Existing WIG craft have generally not been designed from a marine perspective and have not possessed much ability to withstand adverse waterborne conditions. Most of the current design data for the airborne regime are derived directly from traditional aeronautical sources, as WIG typically utilise wing and fuselage geometries derived from traditional aircraft. As all of the previously described designs have experienced serious crashes, it may be that these aero-derivative forms are not best suited for the specific near-ground flight envelope.

The largest-ever WIG, the Soviet KM, crashed and sank in December 1980 due to pilot error. Excessive pitch-up led to a steep climb with subsequent roll, followed by an uncontrolled descent due to throttling back the engines and loss of lift outside of the GE flight envelope, leading to water impact and structural failure causing the vessel to sink. There were no reported injuries to the crew.

Follow-on craft also experienced difficulties, as seen with the Orlyonok, an otherwise successful design by any measure, which suffered severe cracking that separated the empennage from the fuselage in 1975; and then in September 1992 was involved in another climb and descent incident – however, this time the 40 m altitude that was reached and the subsequent impact with the water surface resulted in an onboard fatality (Komissarov, 2002).

The reverse-delta designs have not been spared either, as the X-114 is reported to have crashed during development and trials when retractable hydrofoils had been fitted. The craft touched the water surface with foils extended, but at a negative angle of attack, resulting in a downward force pulling the vessel into an immediate impact with the water surface. More recently, the commercial AirFish 8 experienced structural failure of the port side wing and possibly tail assembly, after being exposed to strong winds and high waves in the Straits of Malacca in August 2012 (*New Straits Times*, 2012).

A significant technical challenge in the development and commercialisation of effective GE craft is therefore their longitudinal stability and seaworthiness, including sufficient robustness of structure. While it is relatively straightforward to propose an efficient aerohydrodynamic configuration with fixed attitude and speed in a steady condition, it is much more difficult to ensure its motion stability and seaworthiness.



Figure 1-11 Photos of the damaged WigetWorks vessel, at sea awaiting tow (upper) and once returned to the quayside (lower). Note the extreme angle of the horizontal stabiliser indicating structural failure of the tail section

1.2.2.2 Take-off Powering

The high power required for take-off has proven to be one of the greatest impediments to the development of the airplane-style WIG (Rozhdestvensky, 2006) as hydrodynamic resistance quickly becomes the largest contributor to overall vessel drag during the transitional phases. This limits operation in increasing sea states and has often led to installed power far in excess of cruise mode requirements.

Hydrodynamically, this geometry has limited availability for water-contacting surfaces and effectively carries a boat hull faired into the underside of the fuselage. This leads to less-than-ideal hydrodynamic performance at high speed, as the longitudinal centre of

mass is too far forward and the vessel cannot adopt an appropriate angle of running trim for effective planing. The inclusion of stepped planing surfaces addresses this issue by decreasing total wetted surface area and moving the hydrodynamic centre of pressure forward, as multiple planing contact patches are created along the hull length. Once parameters such as intended speed, geometric features of deadrise angle and chine beam, and longitudinal weight distribution have been determined, suitable step positions for minimum resistance can be determined (Clement and Pope, 1961).

Hump speed is a marine term that refers to the range on a resistance curve where a localised peak is formed as a hydrostatically-supported displacement vessel attempts to climb over its own wave system and subsequently out of the water. This wave system is composed of a pressure field around the bow and a suction field around the stern; the interaction of these two sub-systems produce constructive interference for coincident crests that act to increase wave-making or destructive interference when crests are out of phase with each other resulting in decreased wave-making. The magnitude of the resultant peaks are dependent on the geometry and initial displacement of the vessel, as well as the forward speed (Rawson and Tupper, 2001). Several techniques have been developed to reduce the main wave-making resistance peak and resulting power requirements, including the fundamental concept of multihulls consisting of two or more demi-hulls of slender proportions (Irens, 2004).

A technique pioneered in the SM-2P prototype was to mount special ‘bow thruster’ engines forward that directed their exhaust under the main wing. Once trialled in this prototype craft, all of the subsequent Soviet designs utilised this technique of so-called Power Augmented Ram (PAR). As these were all high-speed WIG, attaining sufficient speeds for take-off was an ever-present challenge. Their general arrangements were reminiscent of typical aircraft layouts but GE operation presented very different take-off and landing conditions. Firstly, conventional aircraft experience much less rolling resistance from tyres on tarmac than the hull-shaped lower fuselage powering through water. Second, and perhaps more importantly, the technique of rotation upon reaching suitable climb-away speed was not possible, limiting the maximum lift available in this condition. Therefore, the ratio between take-off lift coefficient and cruise lift coefficient had to be more carefully considered.

Figure 1-12 illustrates representative resistance curves for airplane-derivative WIG craft and the effective drag reduction when using the PAR technique. This data was compiled from recorded experiences with the Soviet and Russian Navy (Komissarov and Gordon, 2010). Often, the booster engines would only be used during take-off, then powered down during cruise phases as separate engines were installed, typically mounted aft and sized according to cruise requirements. However, in spite of the disadvantages of installing booster engines for the relatively short time spent in the take-off phase, the characteristic bow thrusters remained a feature of this type throughout their development.

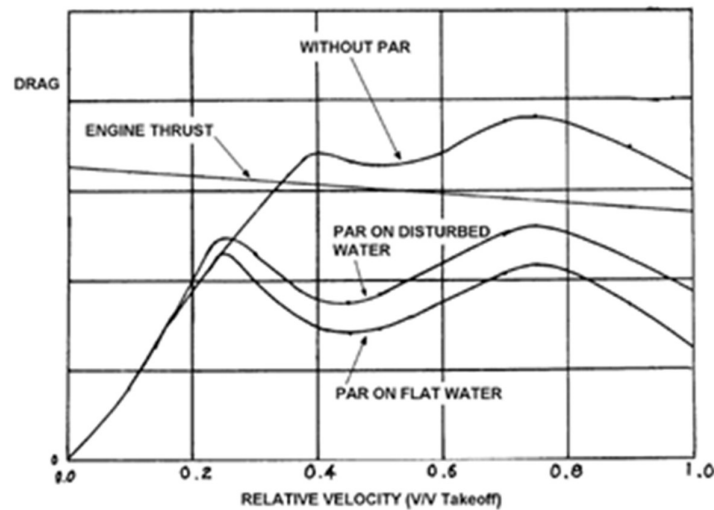


Figure 1-12 Resistance curves illustrating reduction in power required using PAR

Similarly, the technique referred to as Dynamic Air Cushion (DAC) uses efflux from forward mounted propulsors directed under-wing and encapsulated by deep sidewalls or endplates to maintain a high pressure region similar to conventional SES. This high pressure region, or air cushion, provides a significant amount of static lift to support the craft during manoeuvring and take-off.

The fundamental concept of dynamic air injection is shared by both types. DAC is often understood to be more suitable for very small craft due to their ability to operate proportionately closer to the water surface. Derivatives of this type include craft that

generate a static air cushion that permit hovering above the surface at a zero-speed condition.

The majority of existing WIG designs utilise planing surfaces to reach the speeds required to initiate aerodynamic lift. Whilst this may be the simplest arrangement to incorporate into a prospective design, it has contributed to the difficulty of take-off in waves, often exacerbated by unfavourable running trim. The transitional phases of take-off and landing are frequently categorised as one of the most difficult parts of WIG design, with sea state and environmental conditions given as primary factors (Rozhdestvensky, 2006; Yun, Bliault and Doo, 2010); therefore performance improvements in this area would be of foremost importance for a new design concept.

1.2.3 Structural Considerations

The first generation of large Soviet WIG craft employed an aeroplane-style configuration, as previously described. This provided for ideal placement of main wing and tail surfaces, and this layout was presumably influenced by aeronautical engineers who would be familiar with how to design and construct this type of craft.

However, one of the key differences between WIG craft and GA aircraft is the proximity to the sea surface during all aspects of operation. Conventional aircraft are only intended to make contact with the ground by way of a specifically-designed undercarriage, whereas the potential for contact with the water surface is ever-present. The most critical mechanical loading on a WIG craft occurs upon contact of the bottom with the sea surface (Nebylov and Nebylov, 2008).

Striking the rear section of fuselage can induce very high bending moments on the lightweight structure and unfortunately ended up being the main cause of structural failures on all of the early craft, see Section 1.2.2.1. Even the most modern and latest generation WIG can experience the same structural failures in a similar location, see Figure 1-11.

There is no doubt that the structural requirements for designing lightweight but strong structures are not easily satisfied, and as typical aircraft structures have been mainly

aluminium, it is possible that modern composite construction and computational structural analysis could be employed to withstand larger impact forces (Jeong, Han and Kang, 2010). This also comes at additional cost, not just financial but regulatory and safety aspects such as inspection and maintenance throughout the life of the vessel.

As the loading case for incidental surface contact is vastly different for any sea-going vessel compared to one which only travels through air, the shape and overall configuration could be optimised to minimise impact loading. Planform geometries that resemble circles, squares or stout triangles and do not require slender cantilevered structures (e.g. conventional wings, tails or even long fuselages) would inherently result in a more robust structure. Disc-type planforms that could incorporate various twist and camber profiles have been suggested for minimising induced drag or achieving a favourable placement of centre of pressure (Tuck and Lazauskas, 2004).

Slender structures generally fail due to bending moment stresses, which can be many times higher than shear stresses depending on the geometry. Bending moments can be reduced by creating structures that are not only more stout (i.e. less slender) but also have a greater section thickness.

Blended Wing Body (BWB) design concepts have been produced in the aeronautical field that could potentially be adapted to function in the GEZ (NASA Facts, 1997). By incorporating the payload volume into the main wing-body volume, several advantages for WIG operation become immediately available, in addition to the enhanced structural robustness.

Firstly, the resultant low AR wing would have a chord line of the same approximate dimension as the span. Whilst this is generally not desirable in free flight conditions, low AR wings suffer much less of a penalty IGE (Fink and Lastinger, 1961). The main advantage of the long chord is to permit the WIG craft to operate at a greater height above the surface in absolute terms, whilst maintaining low relative height in the GEZ.

Additionally, if the buoyant part of the vessel were arranged in a multi-hull configuration, demi-hulls placed on the outboard edges would act as endplates that aid in containment of the over-pressure zone under the wing-body (Park and Lee, 2008).

Finally, the large internal wing volume could then be utilised for payload, e.g. passenger spaces, in more comfort than the cramped cabin of a conventional small fuselage. An example of this type of vehicle can be found in James and Collu (2015b).

1.2.4 Control Theory & Methods

As described in the previous sections, all functional WIG craft have incorporated tail control surfaces, either as conventional main wing plus tail or in a tandem wing configuration. A primary advantage of the conventional arrangement is that the duties of lift provision and attitude control are independent to a much larger degree, which aids in design and operation of these craft.

Studies into static and dynamic stability characteristics have included OGE tail control surfaces set at a slightly larger angle of incidence than the main wing to be beneficial in ensuring safe and efficient operation (Chun and Chang, 2002). No studies were found that attempted the same analysis for a tailless configuration.

It is known that flight in the GEZ is often accompanied by negative pitching moments which have been shown to be the result of ram pressure acting under the wing (Carter, 1961). This occurrence is more pronounced for craft with low AR planforms due to chord-dominated GE.

However, these pitching moment changes IGE experienced by GA aircraft with low AR wings during landing or take-off are typically not difficult to control with standard control surfaces and has not been considered of first-order importance (Rolls, Snyder and Schweikhard, 1966).

For WIG craft, minimising tail volume could prove advantageous as this control surface invariably operates OGE. The tail is therefore not affected by GE force and moment changes, which aids in maintaining control. This also means that there is no benefit, such as improved efficiency, for this surface.

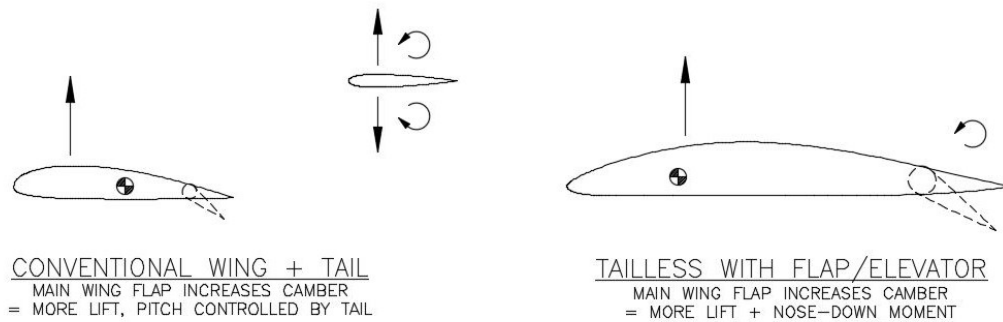


Figure 1-13 Diagram of control methods for wing + tail compared with tailless

In a similar fashion to tailless aircraft operating in free-stream conditions, the main wing must be able to provide the necessary control input, generally being fitted with flaps, ailerons and elevators, or combinations thereof.

As this is intended to be a brief overview of existing methods, no attempt will be made to quantify the performance of these devices IGE, or to assess their complex interactions with the ground plane.

It must be noted however, that tailless or reduced-tail WIG craft must have a sufficiently robust control system to maintain appropriate height and trim not only in cruise conditions, but also in take-off and landing phases where high-lift devices (e.g. flaps) are typically deployed. As shown in Figure 1-13, the effect of rear-mounted flaps on moment balance is far from negligible.

Existing analytical tools for high-level WIG modelling, such as the non-linear vortex lattice method (NLVLM) code Autowing, already include provision for alternative control devices in the aerodynamic and hydrodynamic domains, e.g. hydrofoils. It may be possible to validate novel configurations combining these domains, e.g. hydrofoil lift during take-off, or simply adding non-conventional surfaces such as forward-mounted canards to offset the changes to GE force and moment distributions.

1.3 Aero-hydrodynamics

This section will introduce some relevant concepts for the design of a vehicle that is governed by both aerodynamic and hydrodynamic phenomena.

1.3.1 Governing Aerodynamics

In general, aerodynamic performance characteristics are strongly influenced by wing profile, AR, the presence of other lifting and control surfaces, and characteristic geometric features. Higher AR planforms are known to be effective in increasing aerodynamic efficiency. However, there are various factors that limit GE wing span in practice. Certain manoeuvres applicable to all WIG craft, such as roll or banking in a turn, are limited by wing span and height above surface. Some WIG types rely on a dynamic air cushion under the main wing, where a more compact platform has been shown to be more effective. Additionally, wing span may be limited by port facilities or other navigational restrictions where the vehicle is intended to operate.

1.3.1.1 Height Stability

All GE vehicles require inherent stability in the vertical direction to avoid constant correction to the ground clearance. In WIG craft, the total lift force generated is a function of both Angle of Attack (AoA) and height. In the general case, lift force increases as ground clearance is reduced. Stability is achieved when a decrease in height results in an increase of lift, or equally that an increase in height results in a decrease of lift, restoring the craft to the original height.

Conversely, a craft would be considered unstable in height if, in the event of a disturbance from an equilibrium condition, an increase in the total lift force acted to amplify a change in height. In this case, if greater lift were to cause AoA to increase, which would result in an even greater increase in lift, the craft would quickly become uncontrollable. Similarly, if a decrease in height resulted in a decrease in lift, an acceleration towards the surface would result.

The position of the vehicle Longitudinal Centre of Gravity (LCG) plays a pivotal role in determining height stability. Dependent on the positions of the centre of lift and LCG, a change in speed may result in a change in AoA and/or a change in height. Typically, a speed change IGE would be accompanied by a corresponding alteration to effective AoA to maintain the desired surface clearance.

Longitudinal pitch stability has been identified as one of the key design parameters that are critical for success of WIG craft. The necessary proximity of the ground plane requires sufficient stability and control to avoid unintended physical contact with the surface. To achieve ideal aerodynamic efficiencies, the design condition would be centred on flying heights not more than 10% of the wing chord, as measured from the horizontal ground to the trailing edge of the foil (Korolyov, 1998).

This proximity also complicates the equilibrium states necessary for stable operation, introducing the concept of an aerodynamic centre in height in addition to the more recognised and understood aerodynamic centre in pitch.

Many existing WIG craft have adopted fixed wing aircraft configurations, with identifiable fuselage, wing and empennage structures. Due to longitudinal stability requirements, many utilise a large horizontal wing as a tail control surface, and this additional element decreases the overall aerodynamic efficiency of the vehicle. In order to minimize the size of the tail, S-shaped mean camber profile families have been designed (e.g. the DHMTU series) specifically for WIG configurations.

Another solution has been to adopt a reverse delta configuration for the wing (i.e. Lippisch-type configuration). Despite the fact that a reflexed aerodynamic profile and a reverse-delta wing plan area have a lower efficiency than a clean profile with normal camber and plan area, they allow a substantial reduction of the tail horizontal area required, leading to an increased overall vehicle aerodynamic efficiency.

1.3.1.2 LCG, Aerodynamic Centres & Stability

The mathematical approach for the determination of pitch and height stability for GE wings was begun by Kumar (1967) in his research at Cranfield College of Aeronautics, where the basic problem was framed and investigated. It was shown that there is a change of pitching moment about the vessel Centre of Gravity (CG) with a change of height above ground, and what is termed a change in the position of the Aerodynamic Centre with Height (ACH) above ground.

In a translated work from the original Russian, Irodov (1974) clearly laid out the equations of motion showing that to ensure aperiodic (i.e. static) stability near the ground plane, the focus in height above the ground must lie upwind of the focus with respect to the angle of attack. The work also states that to provide for oscillatory (i.e. dynamic) stability, vessel CG must be centred appropriately between these two locations. These two criteria taken together lay the groundwork for the safe design of the WIG vehicle.

Similarly, a translation of the German work of Staufenbiel and Yeh (1977) presents a mathematical development of the constitutive equations for static and dynamic stability in pitch and height with respect to speed. It is shown how the classical aeroplane derivatives are not sufficient for stability in the vicinity of a ground plane and additional conditions are derived in a simple manner but with profound impact for the WIG designer. The effective design position of the LCG is shown to not impact the vessel static height stability, but its careful placement is critical for the prevention of rotational and vertical oscillations.

For any wing to be stable in flight, the response to any disturbance from an equilibrium steady state should be to return to the original position. Therefore, the wing must satisfy:

$$\frac{dC_M}{d\alpha} < 0 \quad (1-3)$$

where dC_M is the change in pitching moment and $d\alpha$ is the change in AoA

The phenomenon of ground effect, by definition, states that there is an increase in lift as the distance to the ground plane decreases. For this to be the case, the stable wing must satisfy:

$$\frac{dC_L}{dh} < 0 \quad (1-4)$$

where dC_L is the change in lift coefficient and dh is the change in height

Irodov in the U.S.S.R. and Staufenbiel & Kleinedam (1980) in Germany independently further developed the mathematical framework to investigate static and dynamic longitudinal stability of WIG vehicles. It was shown that there is a change of pitching moment about the vessel CG with a change of height above ground, and what is termed a change in the position of the aerodynamic centre with height above ground. To ensure static stability, the relationships must follow:

$$\frac{\frac{dC_{M\alpha}}{d\alpha}}{\frac{dC_{L\alpha}}{d\alpha}} - \frac{\frac{dC_{Mh}}{dh}}{\frac{dC_{Lh}}{dh}} < 0 \quad (1-5)$$

Equation (1-5) can be simplified to show the position of the pitch and height centres must be located so that:

$$\bar{x}_p - \bar{x}_h > 0 \quad (1-6)$$

where $\bar{x}$ indicates the position of the aerodynamic centres in pitch p and height h , as measured from the leading edge, normalised against chord length

Whilst the requirements for static stability do not dictate an absolute position of the CG, it is required to be located between the centres of pitch and height in order to avoid dynamic instability (Irodov, 1974; Staufenbiel and Yeh, 1977).

Figure 1-14 shows a graphical representation of the necessary positions of the aerodynamic centres in pitch and height, and body CG for airborne stability near the ground. The implications of these relationships are fundamental to the stability of WIG craft.

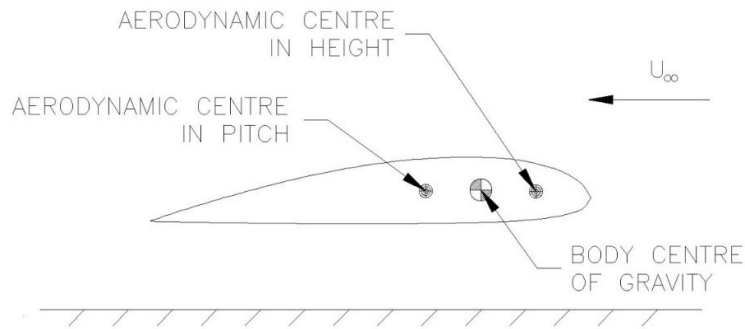


Figure 1-14 Positions of aerodynamic and weight centres for longitudinal stability

1.3.1.3 Reflexed Camber Sections

Although conventionally cambered airfoils can display good lift performance across a range of AoA and heights, they also produce a nose-down pitching moment. This moment requires additional control surfaces to ensure stable equilibrium for a given loading condition IGE. Typically, these control surfaces have taken the form of aft-positioned tails, as seen on conventional GA aircraft. These tails are placed OGE to ensure that the resultant control forces are not height-varying. This reduces the efficiency of the WIG craft as the tail produces additional drag, increases total weight, often requires a larger main wing due to the direction of the control forces, and does not take advantage of any lift increase or drag decrease due to GE.

Alternative airfoil profiles may be more suitable IGE due to their ability to generate a satisfactory lifting force but with a smaller moment, or ideally a nose-up pitching moment. The positive (nose-up) moment would allow for a tailless configuration that retains static stability, as shown graphically in Figure 1-15.

Both the (A) and (B) series begin in an equilibrium condition, with the vertical lifting force equal to the vessel weight and the aerodynamic pitching moment taken about the aerodynamic centre equal but opposite to the moment created by the product of the lift force and the distance from the vessel LCG. When a disturbance from equilibrium occurs, e.g. due to wind gust or pilot input, an increase in AoA will result in greater lift which

can increase AoA further still, as shown in series (A). This is the primary cause of high-speed powerboat longitudinal flip events. Not only is the LCG positioned too far aft for these craft to be stable in flight, but also the situation is exacerbated by the tip of the propeller in the water, creating drag and becoming the fulcrum for body rotation.

In the case of series (B), the lift increase due to the pitch-up disturbance is applied to the craft aft of the LCG and therefore causes a nose-down moment. This additional moment restores the vessel to the equilibrium attitude.

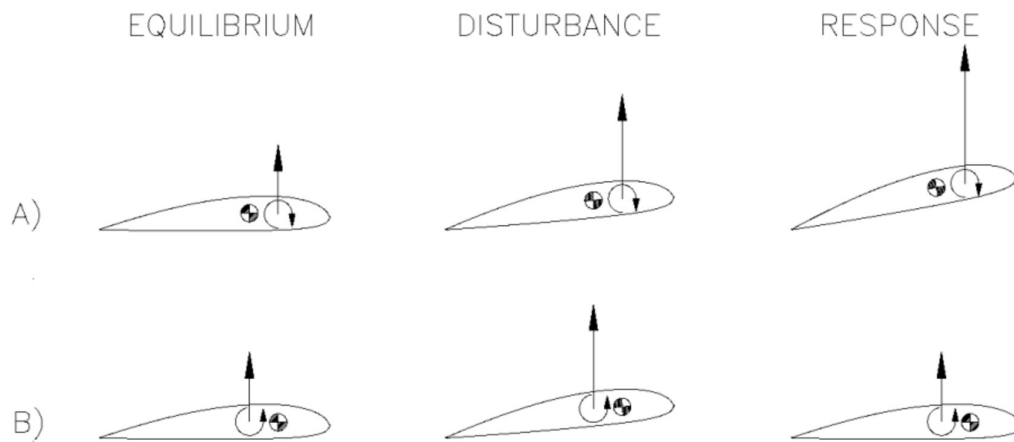


Figure 1-15 Disturbances from equilibrium result in instability in the upper series (A) and stability in the lower series (B)

The magnitude of the pitching moment of a section with reflex, or reverse curvature, of the camber mean-line should be reduced compared to a conventionally cambered section. A typical profile incorporating a reflexed camber line is the NACA 25112. This 5-digit series profile shares similarities to the 4-digit NACA 4412 with 12% thickness, although the location of maximum camber is further forward, at 25% of the chord length from the nose radius. The lower surface of this profile has a relatively constant offset from the chord line, resulting in a flatter bottom without droop at the forward end.

The straighter lower surface might be expected to perform better at very low AoA IGE, without causing downward suction attributed to convergent-divergent flow restriction when placed close to the ground plane. The overall effect of the reflexed camber line

should be to reduce nose-down moment, but at the cost of reduced lift and potentially increased drag.

A family of airfoils specifically for WIG use was developed by the Department of Hydromechanics at the Marine Technical University, St. Petersburg (DHMTU) for the next-generation ekranoplan program. These profiles are characterized by a reflexed camber line and flat, horizontal lower surface. Coordinates of these profiles are not currently in the public domain and detailed information of their construction is scarce.

The coordinate offsets for a 12% thickness section were uncovered through private correspondence. These coordinates have been included in Appendix 8.5. The quasi-lenticular 10-40.2-10.2-60.21.5 profile also includes a small nose radius and long flat section along the lower surface.

The profile naming convention is derived from the physical characteristics in the manner shown in Table 1-4 (Moore, 2004).

Table 1-4 DHMTU profile naming convention

DHMTU aa-bb.c-dd.e-ff.gg,h	
aa	Maximum ordinate of upper surface [%]
bb	Position of maximum ordinate [%]
c	Ordinate at start of flat on lower surface [%]
dd	Position of start of flat on lower surface [%]
e	Ordinate at end of flat on lower surface [%]
ff	Position of end of flat on lower surface [%]
gg	Slope parameter of upper surface to trailing edge
h	Nose radius parameter

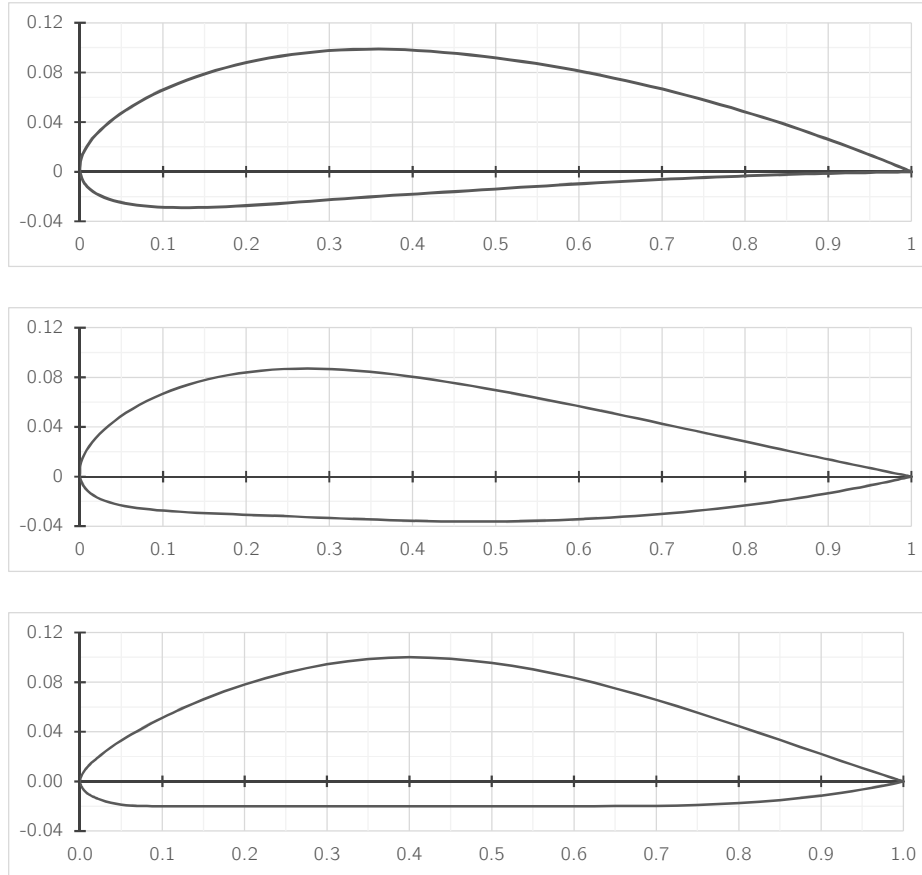


Figure 1-16 Airfoil profiles, from top: NACA 4412, NACA 25112, DHMTU 10-40.2-10.2-60.21.5

1.3.1.4 Existing GE data & experimental results

Little data has been published regarding computational analysis or experimental testing of airfoils IGE when compared to unbounded flow conditions. This is perhaps surprising as the presence of the ground surface greatly influences the domain extents, mesh configuration and selection of boundary conditions for numerical analysis, and the physical constraints of tunnel width, wing attachment and boundary conditions at the ground surface for experimental procedures.

Reference values for GE conditions vary significantly in the literature, even showing trends that are opposite to known empirical and experimental evidence, such as reduced

lift and increased drag as the ground plane is approached at positive AoA (Ahmed, Takasaki and Kohama, 2007).

In their paper, Ahmed, *et al.* experimentally tested a NACA 4412 profile in a wind tunnel with moving ground, with particular emphasis on replicating two-dimensional flow. Lift and drag forces were measured, as well as the pressure distribution over the upper and lower surfaces of the airfoil. Endplate dimensions were carefully selected to replicate purely streamwise flow, not only restricting the formation of tip vortices that would cause an outward spanwise tendency, but also ensuring their presence did not introduce an inward spanwise component. In spite of this seemingly careful set up, many of their published results are quite contrary to what is known about the increased aerodynamic efficiency IGE.

These results and those of several others will be addressed in greater detail in Section 2.2.2.1 and 2.2.2.2.

The most common airfoil profile assessed IGE was found to be the NACA 4412 cambered airfoil, one of the very few profiles that has been compared experimentally and numerically, both IGE and in unbounded flow, with published results in the public domain. Additionally, this profile utilises an almost flat lower surface, seemingly beneficial in ground effect situations where an unwanted Venturi effect may be created under a surface with greater curvature, such as that found on a symmetrical NACA section.

1.3.2 Governing Hydrodynamics

Achieving the suitably high speeds required for take-off has typically been achieved through the use of hard-chine planing hullforms faired into the underside of the main fuselage. This geometry presents several significant disadvantages, such as extreme accelerations resulting from slamming and wave impact, strict longitudinal centre of mass (LCG) constraints with severe resistance penalties for forward locations, and inefficient operation at lower non-planing speeds.

In recent years, many high-speed craft have been constructed utilising slender hull geometries to minimise wavemaking resistance, as this constitutes the largest component of overall drag at these speeds. Several of these vessels have been monohull, as developed by the Very Slender Vessel (VSV) concept (Irens) although the majority have been in a multihull arrangement. From a design perspective this brings the major advantage of separating hull resistance and powering from stability considerations.

1.3.2.1 Performance Criteria for Hydrodynamic Surfaces

The high power required for many types of WIG to achieve take-off is one of the most significant impediments to the development of this type of vehicle (Rozhdestvensky, 2006). In this condition hydrodynamic resistance is the largest contributor to overall vessel resistance due to the density of water being over 800 times greater than the surrounding air.

1.3.2.1.1 Seaplane Floats

The water surface has historically been an obvious place to launch aircraft, eliminating the need to build runways and providing a flat unobstructed surface, when calm. An entire class of fixed-wing aircraft known as seaplanes, including floatplanes and flying boats, evolved and thrived with the need to travel and land in austere ports, until around the post-war period. Therefore, seaplane floats are an obvious source for investigation when considering the hydrodynamic aspects of WIG craft.

A systematic test series of five hullforms suitable for use with single-float seaplanes was documented in the late 1930s, where several combinations of attributes were tested that included stepped planing surfaces, elongated bow fairings, varying chine heights and beams, modifications to buoyancy distributions and tapered afterbodies for drag reduction. The experimental tests were compared to known performance characteristics of the US Navy Mark V float with conclusions drawn correlating certain design features with performance results (Parkinson and House, 1938).

For seaplane usage, floats can be positioned wherever demanded by other parameters laid down during the aerodynamic design of the aircraft. The floats simply need to allow the

craft to achieve the speeds and rotation angles necessary for the take-off and landing phases, once the basic hydrostatic criteria have been satisfied. Although sufficiently stable at lower speeds, floats generally are not particularly suitable for efficient waterborne operation outside of these phases (Gudmundsson, 2013).

For seaplane applications manoeuvrability is generally quite limited on the surface, and any level of seaworthiness beyond the short take-off, landing and taxiing phases is often not required. Fuel efficient operation at lower speeds would be quite poor, primarily due to the high drag of chines, transverse steps and tapered aft sections (Faltinsen, 2005).

Therefore, whilst typical seaplane floats are a useful comparison for high-speed hull design, there are a number of drawbacks and design considerations not applicable to craft that operate successfully on the surface, such that their usefulness would be quite limited for this application.

1.3.2.1.2 Typical WIG Hulls

Support of sufficiently high speeds for waterborne take-off has typically been achieved through the use of recognisably standard hard-chine, hydrodynamically planing hullforms faired into the underside of the main fuselage. There are several obvious disadvantages of this method, namely:

- (a) The overall dimensions of the planing surface must conform to the vessel geometry, most notably the longitudinal aspect ratio (length over breadth) must lie within the constraints of the fuselage dimensions, which may be sized according to other criteria of the design envelope, e.g. minimisation of aerodynamic parasitic drag.
- (b) The longitudinal centre of mass (LCG) must be precisely located for stable WIG operation, although that position is typically much further forward than the location most suitable for planing craft. This would result in excessively high hydrodynamic resistance as the vessel fails to adopt the attitude required to achieve planing efficiencies realised by marine-only vessels.

- (c) Hydrodynamic resistance of beamier geometries can be very high prior to reaching the planing condition, often requiring higher powering configurations to be installed than would be necessary during an efficient cruise condition or any other point of the operational profile. This power is needed to overcome the so-called hump drag.
- (d) Extreme accelerations resulting from slamming and wave impact of the planing hull has been well documented. This has led to structural failures, increase of scantling and structural weights, debilitating injuries to personnel and chronic fatigue to operators and crew. Increase of deadrise is the standard method of reducing these slam-induced pressures, although at the cost of reduced efficiency.
- (e) The planing hullform is also very inefficient at the lower speeds of the displacement and semi-displacement regimes, with resultant powering requirements far in excess of specifically designed vessels operating at similar speeds.

Furthermore, as existing WIG vehicles are typically fixed-wing aeroplane derivative craft that utilise the water surface simply for the take-off and landing phases, they tend to possess extremely limited seakeeping ability or load carrying capacity beyond a few seated passengers. Whilst all HPMV are necessarily limited by adverse environmental conditions, a functional surface-capable WIG craft would aim to deliver typical marine vehicle capability in addition to extreme waterborne speeds characterised by $F_{nL} > 2$.

An example of the impact an unfavourable position of LCG has on planing vessel drag can be seen in Figure 1-17. The Savitsky method (1964) was used to analytically determine hydrodynamic resistance for a planing vessel of nominal but representative form, specifically to demonstrate the large drag increases as the LCG position moves forward. The speed regime would be as expected for this type of vehicle, with resistance values normalised against vessel weight. Important to note is that drag increases above $F_{nL} = 1$ for every incremental move forward of LCG, and is approximately double for the forward-most position compared to an optimised rearward position throughout the speed range.

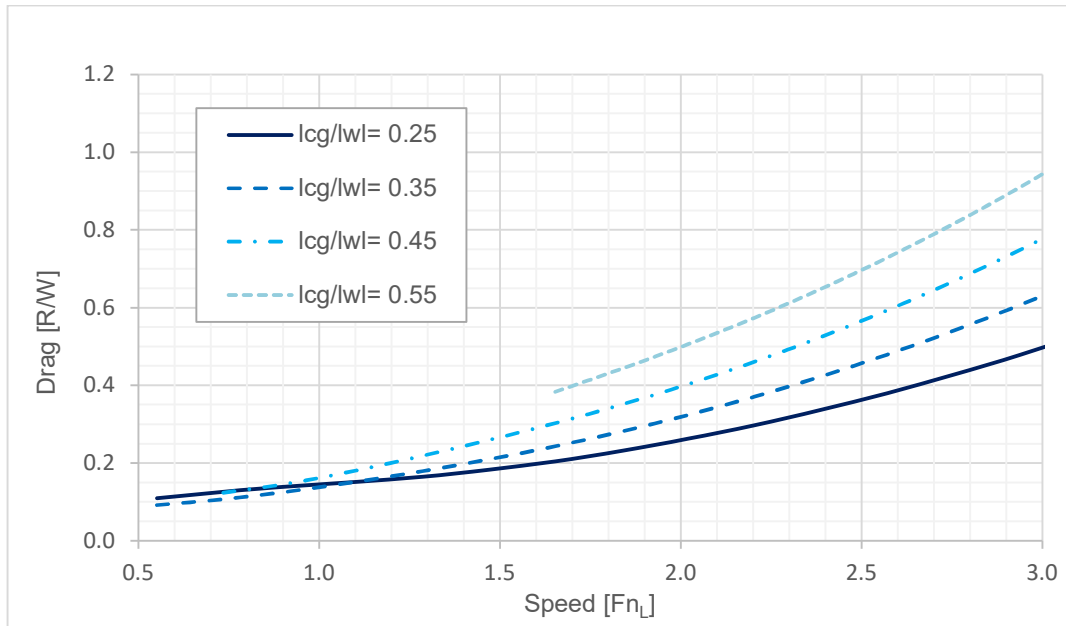


Figure 1-17 Planing hull resistance with varying position of LCG

Additionally, seakeeping effects such as a coupled longitudinal-transverse instability phenomenon has been reported for planing hullforms that cannot maintain suitable running trim due to unusually far forward LCG. The vessel may attain stable equilibrium on-plane in a normal manner, before experiencing a sudden decrease in the running trim angle, whereby the fullness of the bow sections tend to initiate a roll and/or yaw response (Savitsky, 1985). This is generally not a significant concern in conventional marine design, as it would be highly unusual for planing HPMV to have their LCG located so far forward due to practical considerations such as machinery installations, etc., in addition to the excessive resistance and powering penalties.

With these factors taken into consideration, the conclusion indicates an alternative hullform would be desirable, one that could accommodate an LCG position further forward than typically found, but also one that allows that vessel to achieve the required waterborne speeds without excessive powering requirements.

1.3.2.2 Existing Methods for Hydrostatic/dynamic Support

A number of hullforms have been developed over the past several decades mainly for use in high-speed passenger ferry applications. These vessels are typically multi-hulled, with design specifications similar to that required for WIG use, such as being capable of attaining high speeds with reasonable fuel efficiency, and offering comfortable motions through a seaway with minimal slamming and vertical accelerations.

This style of displacement hull utilises a very narrow beam to reduce wavemaking resistance, typically the highest component of drag at high speeds. The half-angle of entrance is very low, often resulting in wave-piercing characteristics. The slender vessel approach has successfully reduced wavemaking drag to the point that skin friction drag usually exceeds all other resistance components in the high-speed range. Several examples of these craft are shown in Table 1-5, with their relevant particulars and performance characteristics.

Table 1-5 Performance characteristics of several slender-hulled high-speed craft

Vessel	Speed <i>kt</i>	LWL <i>m</i>	Power <i>kW</i>	F_{nL} -	Disp. <i>t</i>	Specific Power <i>kW/kg</i>
Francisco (Incat Ferry)	58	90.5	44000	1.00	1065	0.041
X-Craft	55	73.0	45000	1.06	900	0.050
Mary Slim VSV	38	22.5	1230	1.32	15	0.082

As conventional marine vehicles, any lift that is produced to augment the hydrostatic buoyancy forces can only arise from the hydrodynamic flow, yet they are still capable of achieving length-based Froude numbers greater than one. If this type of performance were to be coupled to aerodynamic lifting surfaces, the apparent weight unloading would allow the craft to exceed these speeds as wetted surface is reduced, with very little additional power required due to the density differences between air and water.

Additionally, the slender vessel approach permits more flexibility in LCG position, a critical parameter for WIG operation. However, the performance of planing hulls is known to be closely linked to LCG position, with very large resistance penalties for non-optimal forward positioning. Adverse handling has also proven to be a concern with forward LCG, resulting in the coupled longitudinal-transverse instability phenomenon noted previously.

Therefore, an alternative hullform to the conventional hard-chine planing hull would be desirable, if it could accommodate a forward-positioned LCG without adverse handling or resistance penalties, and allow that vessel to achieve the required waterborne speeds. James and Collu (2015) have presented a detailed description and design rationale for these options.

1.3.2.3 Experimental Hydrodynamic Lift Devices

Hydrofoil assisted take-off has been tried a number of times but appears to have inherent limitations such as the onset of cavitation on the upper surface, additional mechanical complexity, and safety concerns at low altitude and negative angles of attack, rendering the technique less than ideal.

Most notably, the otherwise-successful X-114 trialled hydrofoil surfaces fitted under the buoyancy floats in an attempt to reduce take-off powering. It is not clear if this had the desired effect, as wavemaking resistance may have decreased but the wing distance to the water surface increased with a resultant reduction of aerodynamic lift. The landing phase also became problematic due to the potential for negative angles of incidence with the water surface and resulting generation of a downward force.

Interestingly, there are numerical studies of WIG with a partially-submerged hydrofoil; when hydrodynamic forces are of a similar magnitude to the aerodynamic forces of the main wing, better static stability than the same craft without hydrofoil has been reported (Benedict *et al.*, 2001). However, when hydrodynamic forces dominate, high installed power requirements are required and less than ideal efficiencies (Van Beek, Oskam and Fantacci, 1998). Either way, these results have not been replicated by a physical model of any size.

During the Soviet WIG era, a hydro-ski deployed on a flap under the forward part of the fuselage was used with a fair amount of success. This ski provided good hydrodynamic lift and was shown to have good performance in landing, although the lift-drag ratio was poor (Hudson, Hirdaris and Guerrier, 2009).

1.4 Literature Summary

This introductory section has provided a brief overview of certain aspects of the current body of knowledge in the field of WIG design. By covering the foundational principles and some history of the evolution of this type of vehicle, context has been provided to better understand the current state of the art.

The richest source of theoretical data, exploratory R&D, experimental prototypes and even a few full-size craft would be the Soviet programme carried out under Alexeyev. However, little is actually known about the technical details and engineering databases compiled during this programme, and this information is not available in the public domain. What remains is photographic evidence that shows these craft existed and carried out certain operational manoeuvres. A solitary corroding hulk can still be seen on the shores of the Caspian Sea in Kaspiysk, Russia. Recorded data indicates that the heaviest airborne vehicle until 1988 was a Soviet WIG, with a measured propulsive efficiency factor in terms of powered thrust to vehicle weight unsurpassed to this day.

Perhaps making matters worse, much of the published data that may exist in this field in general is of questionable quality. As something of a fringe topic, papers that get accepted for publication may not fully comply with expected rigorous standards, if for no other reason than there are not many resources for an informed peer-review. The proliferation of online journals has resulted in papers that show conflicting and even contradictory results. Furthermore, even well-researched and well-presented data is often found piecemeal, i.e. a single data point for a given profile at a given angle of attack at a given height. Without a more comprehensive approach it is not possible to utilise this type of data for design purposes.

With this in mind, the following sections will attempt to categorise current research and development into a few broad categories.

1.4.1 Key Weaknesses in Literature

It must be stressed that the scarcity of reliable data is probably the greatest weakness for any potential WIG researcher; this is a recurring theme that runs throughout. It is not particularly clear what is actually known, what is theorised, what might be appropriate under certain circumstances but not necessarily others, what methods can reliably be used in the generation of new data, how to validate any new tool or either numerical or experimental result, and on *ad infinitum*.

There is currently no standardised robust methodical approach to generate reliable GE data, either numerically or experimentally, and no agreed ‘test case’ that any new research can be validated against. This approach is found in other industries to ensure newly-developed tools and methodologies capture sufficient accuracy and resolution.

It is not unusual to find published results between researchers that are not in agreement, usually due to varying methodologies and numerical or experimental approaches. The presence of a ground plane arguably makes set up, data capture and analysis more complex when compared to general aerodynamic research.

Generally, there does not seem to be a core understanding in the research community of the intrinsic mechanisms by which airfoils are affected IGE, beyond noting improved lift-drag efficiency, and no particular mention of how to begin the process of designing a new vehicle or accurately assess its performance. Producing lift, drag and moment diagrams, which is often what is found, is not sufficient in isolation but certainly provides a firm foundation to develop a deeper understanding of the subject.

The breakdown into the following categories has been selected to fit the available data that has been collated. As a multi-disciplinary topic, this arbitrary selection of headings should prove as valid as any other.

1.4.1.1 Mathematical Models

The earliest attempt at a mathematical model of airfoil behaviour IGE, was found to be from Cranfield in 1967, as described in Section 1.3.1.2. A new concept was introduced, that of a neutral point with reference to height above ground, *viz.* a point where a pitching moment coefficient does not vary with lift coefficient, in the same manner as the neutral point with reference to angle of attack, which is commonly referred to as the aerodynamic centre. This new concept was termed the aerodynamic centre in height. It is important to note that the conventional aerodynamic centre is a useful construct for design purposes to avoid recalculating centres of pressure for every incremental change in pitch.

It was not specified how the position ACH is to be combined with the position of ACP, or even whether such a point actually exists outside of mathematical analysis. Subsequent work in the Soviet Union and Germany also made use of this concept and even showed relationships between longitudinal positions of ACP and ACH to define longitudinal static stability IGE.

There was still no information on how the ACH was to be incorporated into a physical design. Furthermore, it was not made clear whether it is even possible to design an airfoil with the characteristics as described. In every engineering endeavour there are design drivers that must be adhered to for whatever reason, e.g. technical, operational, financial, etc., and other attributes that are preferable but not necessary. If preference must be given to either ACH or ACP, which of these is the design driver must be known.

Some decades later another mathematical framework was developed at Cranfield, when it was attempted to model the transitional and airborne flight phases, whereby the dynamic model required accurate aerodynamic coefficients across a range of angles and heights. This data was not available in sufficient resolution.

Several researchers including Collu, Patel and Trarieux (2010), Matveev and Kornev (2013) among others, have subsequently developed complex mathematical models to explore GE behaviour. However, one of the main shortcomings remains locating accurate data for inputs to such a model.

The concept of ACH remains obscure, there is no data indicating validation by experiment, therefore it is not clear if this is truly a required physical law of geometrical relationships or an interesting mathematical curiosity.

1.4.1.2 Computational Methods

There are studies available that have investigated wing performance IGE, although much of the numerical data disagrees on the magnitude of the aerodynamic forces. The NACA 4412 appears to be the most researched airfoil profile for this application. This does not mean it is well-suited to this usage, however. As there is some amount of existing data, this makes it more likely to be selected to begin initial study and methodology validation. Nevertheless, other than this single profile, there is extremely little data available, most of which is piecemeal and much is of dubious quality.

Rigorous standards have been developed for freestream aerodynamics, including guidance on domain extents, boundary conditions, first layer height and inflation layer growth, turbulence modelling, meshing and blocking techniques, etc. The majority of GE research does not adhere to these standards. Furthermore, it is not clear if the same standards need to be applied IGE, as the presence of the ground plane may stabilise certain factors, while equally possible, exacerbating others. It is not even possible to adhere to every guideline, as freestream aerodynamics takes place sufficiently far away from any surface for its effect to be rendered negligible. Various published results showed computational domains that could be considered inadequate, with cavalier approaches to cell discretisation and flow characteristics, yet having produced results that are reasonable and in keeping with GE theory.

As there is no test case for GE simulations, it can be difficult to assess whether a given approach is satisfactory. One may achieve functional results in part of the GEZ but have the model fail in others, especially in EGE. A given profile may prove satisfactory and another less so. A robust numerical model must be stable across different profiles, for a wide range of angles, across the range of heights of interest. There is currently no guidance on how to achieve this.

Complicating matters further, defining the reference point for measuring heights has two differing systems, either at the aerodynamic centre or at the trailing edge. Conversion

between the systems can be attempted using classical mechanics theory, although typically the results will not be comparable as the moments and lift forces due to height will be for a different configuration.

1.4.1.3 Experimental Methods

For validation of GE performance and analysis of potential new designs, reliable experimental data in this region is necessary (Ockfen and Matveev, 2008). The majority of experimental procedures for this process utilise wind tunnels with some form of boundary layer management, typically boundary layer suction. This is required to maintain zero velocity differential between the tunnel windspeed and ground surface. Unfortunately, this is generally not easy to implement and can be the source of considerable error, especially when the distance from the airfoil to the surface is small. The specifics of how to achieve a satisfactory pressure gradient in practice, that is suitable for high resolution GE research, is beyond the scope of this project.

Reynolds number matching becomes another significant challenge in the wind tunnel. As the goal is to achieve dynamic similarity with full-size flow regimes, tunnel velocities should scale directly with model scale factor, quickly resulting in flow velocities approaching transonic and supersonic speeds. This is not acceptable either, as full-size WIG craft typically operate at low Mach numbers where airflow is considered incompressible.

Effects of Reynolds number influence IGE is not a well-researched topic. Documented experiments closely matched to those of numerical results were not found. Experimentally, Re often appears to be an afterthought, if stated at all. It is not clear what effect this has on results, as this aspect has only been investigated numerically. Ideally, experiment at similar Re to full-size would yield the best approximation of fluid flow, including turbulence generation, eddy formation and vortex shedding.

As GE research is at such an early stage, experimental set up typically attempts to replicate 2D flow. Span-dominated effects can then be neglected, to better understand chordwise effects. Endplates are well-known to reduce spanwise flow and have been used with uncertain effectiveness, as it appears that rolling road wind tunnel tests can

produce anomalous results, especially as the distance to the ground is reduced. This is investigated further in Section 2.2.2.1.

No data was found for testing of more advanced concepts such as PAR and DAC, which utilise under-wing blowing to increase pressure differential. It is unknown what research was conducted previously and it may be that the most effective way to test these effects is via large-scale prototype or full-size demonstrator.

1.4.1.4 Hydrodynamic Performance

It was quickly realised that seaplane float design data could provide a performance baseline. Floats were developed to provide hydrostatic buoyancy when on the surface at zero and low speed, and have suitable form to allow the airplane to accelerate to take-off speeds over the water surface. However, these are also known to be somewhat cumbersome during flight mode, as evidenced by the weight fraction and airborne drag characteristics. Additionally, these floats are not effective for general surface operation, as seaplanes typically only require a short taxiing phase to dock once landed. Therefore, alternative forms or methods were sought that would produce similarly favourable high-speed characteristics for take-off and landing but would also allow the vehicle to be more capable during surface operation.

Naval architectural methods of assessment were used to analyse high performance craft, as described in Section 1.1.2. Whilst useful craft in their own right, none of the HPMV seemed particularly suited to WIG applications, usually due to performance penalties, e.g. in the case of standard planing craft, or energy management penalties, e.g. in the case of ACV which utilise separate lift fans.

Typically the operational speed envelope of marine craft is well below that required for WIG take-off. Hydroplanes and other extreme high-performance craft are as weight sensitive as airborne vehicles and are often only viable in very small and lightweight packages. However, recent advances in high-speed multihulls in ferry and other time-sensitive applications indicated that payload might be able to be carried at high speed, especially when the aerodynamic alleviation effect is taken into account. This results in a craft that effectively becomes lighter as speed increases due to the lifting effect of the

wing. These hullforms may also perform satisfactorily in low- to moderate-speed surface operation.

The question is then how to design a suitable hull and how to validate its performance. Marine references generally do not cover the Froude numbers of interest here and experimental craft and cutting-edge vessels, e.g. recent iterations of America's Cup foiling craft, are the result of expensive and laborious developmental campaigns and, perhaps most importantly, do not readily share their data.

Furthermore, there are not many facilities in the UK, or even worldwide, that can test such a model at requisite speeds, and performance predictions and analysis methods are problematic as the craft would be well-outside of industry standard International Towing Tank Conference (ITTC) parameters for their methods.

Testing marine vehicles in a wind tunnel is a possibility due to incompressible fluid flow similarities, although this method may introduce more uncertainties than solutions. Again, very little documentation exists for this method.

Computational fluid dynamics could potentially be used to develop and virtually prototype different hullform configurations but would require a pre-existing code, validated and verified to provide accurate results in a very challenging spray-filled air-water domain. This type of resource was not available for this project.

1.4.1.5 Control Methods

Adequate longitudinal stability and control has been identified as one of the key issues to be addressed by several reputable researchers, generally with reference to crashes that have occurred. How to achieve this stability has received far less attention.

A large horizontal stabiliser outside of the GEZ is an identifiable feature of most WIG craft, albeit with several important drawbacks. Primarily, placing a large surface OGE means there is no aerodynamic benefit due to GE, reducing overall efficiency. Additionally, this surface requires supporting structure and actuation mechanisms which would ideally be lightweight, to minimise rearward movement of structural LCG, and slender, to minimise aerodynamic resistance. Both of these factors contribute to vulnerability of the tail under impact and has been a significant point of failure for several

craft. There is very little mention of this fundamental design weakness or attempts to produce a functional tailless WIG.

A tandem arrangement with two low-mounted lifting surfaces was one of the first prototypes produced by the Soviet programme. It was reported to have good stability characteristics, as expected from the two staggered lifting surfaces. However, this configuration was soon abandoned in favour of a single lifting wing with OGE tail. The tandem arrangement also appears on the Jorg Flairboat design, which operates at significantly lower speeds than the Soviet craft. This is not a configuration that has been the subject of much published research.

There is very little research on alternative WIG configurations that may show a higher degree of inherent longitudinal stability or any attempts to reconcile the static stability criteria between ACP and ACH as set out in the mathematical frameworks. The tandem wing seems to achieve this with all lift occurring IGE but it is not clear if this is possible with a single lifting surface, albeit with potential modifications to profile design and 3D planform effects

It is also not clear if an inherently stable planform should be a key area of research or whether modern flight computer based systems are sufficient to control even inherently unstable designs, as has been the case with conventional aircraft.

1.4.2 Key Areas Not Addressed

There is no evidence that a dual mode aero-marine vehicle has ever been attempted. Sea planes have used the water surface for take-offs and landings but quickly climb out to operational altitude. Even low-flying airplanes usually maintain sufficient altitude to remain outside of ground effect. Equally, the few WIG craft that have been constructed are not capable vehicles on the water surface; ironically, unintended contact with the surface has been the root cause of many accidents and significant crashes.

Even though WIG craft are internationally classified as marine vehicles, there is surprisingly little data regarding hydrodynamic performance and possible improvements that could be achieved over vehicles that have already been built. There is also no

reference to vehicles that could operate as a surface vessel and as WIG, outside of occasional government-sponsored research proposals. Currently, the few WIG designs that exist either use seaplane float geometries or high-speed planing surfaces, resulting in excessive powering requirements during the take-off phase, long identified as a key technical challenge.

Technical challenges such as reducing take-off speed or powering requirements have been identified by experienced WIG researchers but there seems to be very little published information on these topics. Hydrofoils and other known high-lift devices have been proposed for reducing hydrodynamic resistance but generally these have already been attempted, sometimes decades ago, and found to not provide a functional solution.

Structural vulnerabilities such as slender fuselage and tail assemblies are potential weak points for marine design and an alternative design could prove beneficial. Aviation concepts such as Blended Wing Body (BWB) may be repurposed to function in the GEZ, exploiting some of the natural strengths of their compact design. If it were possible for the WIG to satisfy geometric requirements for longitudinal stability whilst utilising a single or blended main wing with suitable planform and profile sections, a vulnerable tail and empennage structure could be discarded. There is currently no research in this direction.

Similarly to the flying wing approach, a wing planform with long chord creates an internal volume that becomes useful for passenger and cargo transportation, even at moderate thickness to chord ratios. As the GEZ definition is normalised to wing chord length, larger overall dimensions result in a vehicle that can operate with a greater height margin for a given sea state. These larger dimensions soon become an obvious location to house the vessel's payload, eliminating the need for a conventional fuselage. Additionally, due to the low flying height, the WIG would suffer no structural penalty owing to any need for cabin pressurisation.

1.4.3 Project Aims & Objectives

This aim of this project is to develop fundamental knowledge and engineering data to be used in the preliminary design of a Wing-in-Ground Effect vehicle. In order to address the weaknesses described in the literature, specific objectives were set out to investigate this subject using a first-principles approach wherever possible.

Three concurrent work programmes are to be carried out, covering experimental testing of a novel hull design, computational analysis of various wing profiles operating in ground effect, an experimental programme to validate an unusual profile using an unconventional towing tank technique, and finally developing a parametric geometry tool to allow the collected data to be utilised in the sizing and powering for generating conceptual designs of novel WIG craft.

The work packages are as follows:

- (a) A hull model is to be designed and built, then towed at high speed to assess its potential performance in the take-off phase of WIG operation. As likely to be a slender hullform, it would also be suitable for waterborne operation at modest speed, leading to the possibility for a dual-purpose vehicle comfortable in air or water.
- (b) Creation of a database of aerodynamic coefficients for profiles suitable for use IGE. This work is intended to provide a reliable database of 2D aerodynamic coefficients by establishing a robust methodology for numerical solution. A detailed range of heights above ground and angles of attack must be included, and the methodology should be easily applied to additional profiles in the future. As this data is very often incomplete or erroneous in published data, development of a robust method is of the utmost importance in this field.
- (c) Establishing reliable experimental techniques for testing wing profiles IGE, one that would be simple to set up and not rely on complexities found in wind tunnel experiments. A physical model wing will be constructed and towed near the bottom of a water tank to replicate the physics and flow

patterns of a wing immersed in an incompressible fluid moving over static ground. The selected profile will also be included in the computational work so the results of the two methods can be compared.

- (d) Finally, a parametric geometry tool is to be developed to explore the design space and assess feasibility of various configurations. Primary components can be sized and positioned with corresponding powering estimates, to generate WIG conceptual designs.

2 Methodology

After reviewing the available literature, it became apparent that several key gaps in the common knowledge base were present. Among those included:

- (a) Hydrodynamic hull forms and/or lifting devices that could reduce the powering burden during the take-off phase (Section 2.1);
- (b) Database of aerodynamic coefficients for profiles suitable for use IGE (Section 2.2);
- (c) Reliable experimental techniques for testing wing profiles IGE (Section 2.3).

These topics have been selected as the main areas of focus and a work plan was developed in order to address them, within the capability of the tools and facilities available, as described in the following sections.

2.1 Hydrodynamic Surfaces

As stated in the literature review, there are several important factors that influence how a craft behaves and operates on the water surface. Simply fairing in a vaguely boat-shaped hull into the underside of a WIG craft is unlikely to produce an optimal configuration that reduces drag and powering requirements during take-off or during surface manoeuvring.

These factors indicate an alternative hullform would be desirable, one that could accommodate a LCG further forward than typically found on conventional marine craft, but also one that allows that vessel to achieve the required waterborne speeds. Therefore, a design brief with the following characteristics was laid out:

- i. Must be able to carry a centre of mass (and therefore centre of buoyancy that maintains equilibrium trim) around amidships, defined as $LCG/LOA = 0.5$.
- ii. Must be suitably shaped to allow high speed operation without excessive powering or undesirable behavioural characteristics, e.g. submarining, yaw instability, excessive slamming, etc.
- iii. Would ideally reduce low-medium speed resistance, as defined by $F_{nL} < 1.0$, to a similar magnitude as conventional efficient semi-displacement hullforms.

Applying this design brief the design of a hull that could meet the specified criteria was carried out. As this was likely to have unconventional characteristics, not typically sought for general marine use, design data and experimental validation was not expected to be found in the public domain. Therefore, it was decided to build and test a small-scale model to verify performance characteristics.

2.1.1 Hullform Development

Recent displacement hullform designs in the multihull sector have introduced slender hull concepts that are able to provide a suitable platform to attain high speeds, whilst minimising the extreme accelerations characteristic of planing craft. Additionally, these hulls are capable and efficient at lower speeds, instead of being constrained to a single design point. This type of flexibility is essential for waterborne performance, as a number of effective displacements, trim angles and powering requirements are experienced during the phases of operation.

The guiding principles would lead to a slender hull, i.e. high length to beam ratio (>10), with Longitudinal Centre of Buoyancy (LCB) well-forward to at least around amidships, with very long waterline but wave-piercing forward sections to minimise wave impact decelerations. Additionally, the hull would have to retain its desirable characteristics at various drafts, as the vessel will heave (i.e. experience vertical translation) as the aerodynamic lift forces generated by the wing increase.

In contrast to conventional planing hulls, where it is common practice to maintain the longitudinal sections straight and flat throughout the after part, there would be significant rocker (i.e. fore and aft curvature) along the entire length of the keel. The idea was that any bow-up trimming moments caused by hydrodynamic pressures may well be advantageous aerodynamically to increase angle of attack on the wing and initiate the weight unloading process, albeit at the risk of inducing downward hydrodynamic suction force. The rocker angle in the buttock lines was closely controlled to match the estimated angle of running trim that could be advantageous during a take-off procedure. Although this angle wasn't known at this point, it was estimated to be around 3° .

Therefore, once a trim angle of approximately $\tau = 3^\circ$ was reached with the bow clear of the water, the buttock lines would become effectively flat. Instead of the deeply veed forward sections of conventional planing hulls, the enclosed volumes were inverted, i.e. somewhat flat-bottomed with topside tumblehome to create a very narrow deck area forward, to minimise the effect of green water holding the bow down. A very short vertical stem maximised waterline length before this ‘cutaway foredeck’ reverse curvature sloped up to where the deck would effectively begin. Figure 2-1 shows a representative lines plan for a hull with these characteristics.

This hullform does not include any chines or spray rails to prevent oncoming flow from rising up the topsides, i.e. to reduce side-wetting. This results in a two-fold penalty of additional wetted surface and viscous drag, and does not take advantage of deflecting this topside flow outwards and downwards, thus generating additional lift. Not including these features allowed a more direct measurement of the fundamental hull characteristics and can be added at a later detailed design stage.

The LCB was situated at 0.5 LWL for the static design draft condition, with the transverse sections configured so this centroid moves forward gradually as the vessels rises bodily. As the location of the centre of mass is not expected to shift significantly during the take-off or landing phases, this misalignment of longitudinal centres should increase the bow-up trimming moment, likely to be favourable for the aerodynamic configuration.

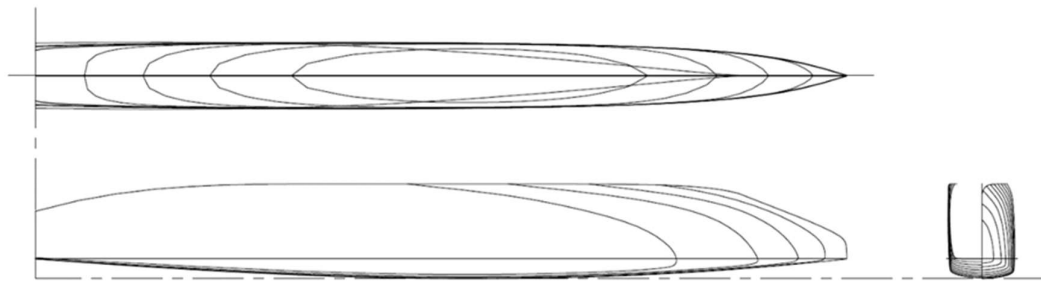


Figure 2-1 Representative lines plan showing plan, profile and body plan views

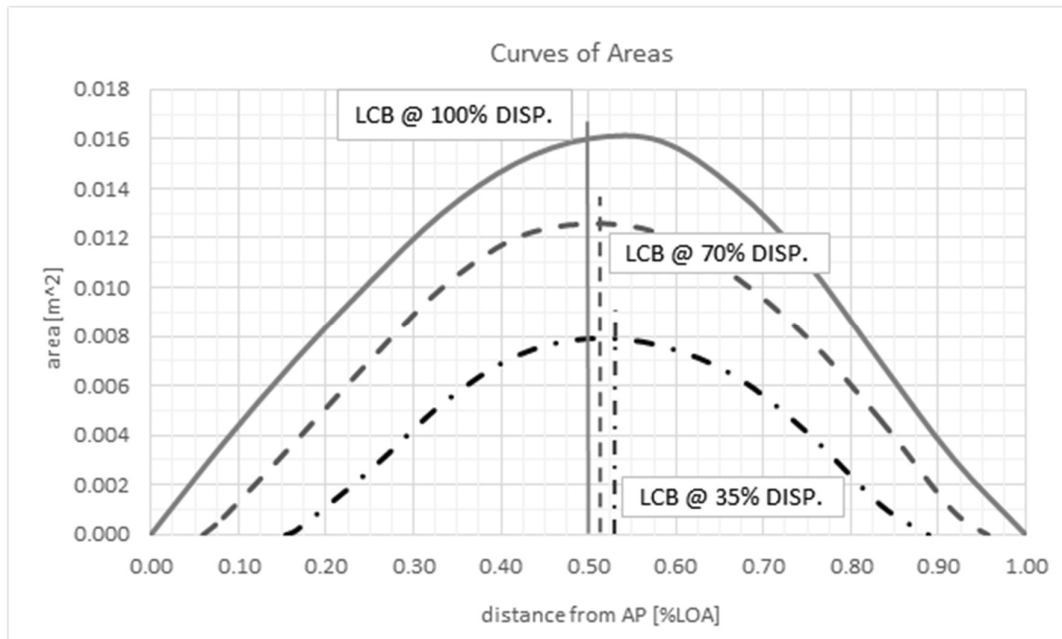


Figure 2-2 Curves of transverse sectional areas for varying displacement conditions

By inspecting the curves of submerged areas of transverse cross-sections along the length of the hull, at full displacement and for reduced displacements, the change in LCB position can be determined. Not only was it important to keep the LCB in a relatively unchanged location but also to ensure there weren't any sudden changes in buoyancy distribution as the hull would be experiencing the effect of aerodynamic alleviation. Figure 2-2 shows the area curves and LCB at three displacement conditions.

2.1.2 Development Tool Selection

Initial design of the new hullform was carried out using analytical naval architectural principles, including analysis of transverse sectional characteristics for hydrostatic buoyancy distribution at various displacements, governing design ratios and coefficients suited to the anticipated performance range, and specific features intended to interact with aerodynamic surfaces that might prove beneficial during high-speed transitional take-off and landing phases.

Computer-aided design methods are commonly used in the field of naval architecture, from the basic tasks of drafting and design documentation, to advanced tasks such as structural analysis, assessment of static and dynamic stability criteria, resistance and powering predictions, even motion prediction in various sea states and manoeuvring characteristics.

Various types of numerical methods are also available to assist with front-end design synthesis. Scripted routines coded in Matlab or Python can be used to rapidly reconfigure geometries that can then be fed through to analysis tools for optimisation within a specified set of parameters. Advanced research methods utilise genetic algorithms and neural networks to generate designs optimised for a given set of criteria.

Computational Fluid Dynamics (CFD) codes have developed sufficiently to solve complex fluid flows with moderate computational resources and can be used in the development process by virtually prototyping different hullform configurations. However, these codes must be rigorously validated and verified for the type of flow solution required. This resource was not available during this development phase and the time, effort and skill required to build a reliable routine would have been prohibitive.

Instead, a potential flow code for slender hulls with far-field wake evaluation was utilised for preliminary resistance prediction, as no suitable regression methods were available. This code was much simpler and quicker in execution than a fully viscous solver, although would not provide the same degree of fidelity. For the current initial stage of preliminary development, the potential flow code was found to be adequate.

If a robust CFD tool had been available for rapid iterations during this process, a more comprehensive exploration of the design space could have been carried out before selection of the final model geometry. A different design methodology could have been adopted, such as exploring various fundamental shapes to assess how they might be suited for the particular use-case of the WIG.

In addition to using CFD methods for resistance predictions, dynamic loading on the body at various headings and encounter frequencies could be investigated to predict force and moment magnitudes. As the hydrodynamic surfaces are rigidly coupled to the aerodynamic wing, it may be possible to introduce synergistic effects that assist in lift generation at critical phases, in order to address one of the recognised difficulties of sufficient powering for take-off.

Detailed design features such as placement of chines, lifting strakes, spray rails, etc., could be incorporated at appropriate positions to reduce drag and enhance lift, although this would necessitate a very well validated high-fidelity code. The air-water free surface has always proved a very challenging environment to model accurately due to the range of length scales from mist and droplets up to large waves and a full-size vehicle.

Taken to the extreme, such a high-resolution computational solver may replace the utility of the towing tank altogether.

This type of resource was not available for this project.

2.1.3 Scale Factor

In order to experimentally test the hullform, a baseline estimate of the full-size geometrically similar hull was required to determine appropriate speeds to be tested. Due to the high-speed nature of generating sufficient aerodynamic lift during take-off manoeuvres, it was readily apparent that appropriate facilities for testing a model of reasonable size were scarce.

The larger the model, less of a scaling factor would be required which is generally considered ideal. In the extreme, a full-size prototype would require no scaling such that measured forces would be the actual forces exerted on the hullform. Additional effects that do not scale easily such as spray generation and behaviour are more accurately represented in a model requiring less scaling.

Therefore, a full-size baseline of 20 m was determined based on overall vehicle geometry, as this results in a useful wing volume that could be utilised for payload or usable internal accommodation. However, the desired take-off speed was unknown at this point. Based on previous WIG types with long-chord planforms, an estimated range between 40 kt and 70kt was established, a range wide enough to allow for comfortable margins if take-off speed needed to be revised at a later date.

An overall model length $LOA_M = 3.000$ m was decided to be the most suitable trade-off in terms of decently large size with sufficient scale factor to allow the tested model speeds to scale up to full-size desired speeds. Although a test facility was not yet selected, in order to test a model of this size in the appropriate speed range, a maximum carriage speed of around 12 m/s would be required.

As such, the model was designed to be suitable for scale factors between 5 and 10. Depending on the scale factor selected, a carriage speed of 12 m/s would correlate to a maximum full-size speed between 52 kt and 74 kt.

Appendix 8.3 details all of the model parameters and upright hydrostatics for 0° and 3° trim conditions. A brief summary of principal dimensions is presented in Table 2-1.

Figure 2-3 shows the range of speeds covered for the indicated scale factors.

Table 2-1 Principal model dimensions & design ratios

LOA	Beam _{WL}	Draught	Δ_{DES}	C_P	C_B	C_M
<i>mm</i>	<i>mm</i>	<i>mm</i>	<i>kg</i>			
3000	243	75	30	0.611	0.536	0.889

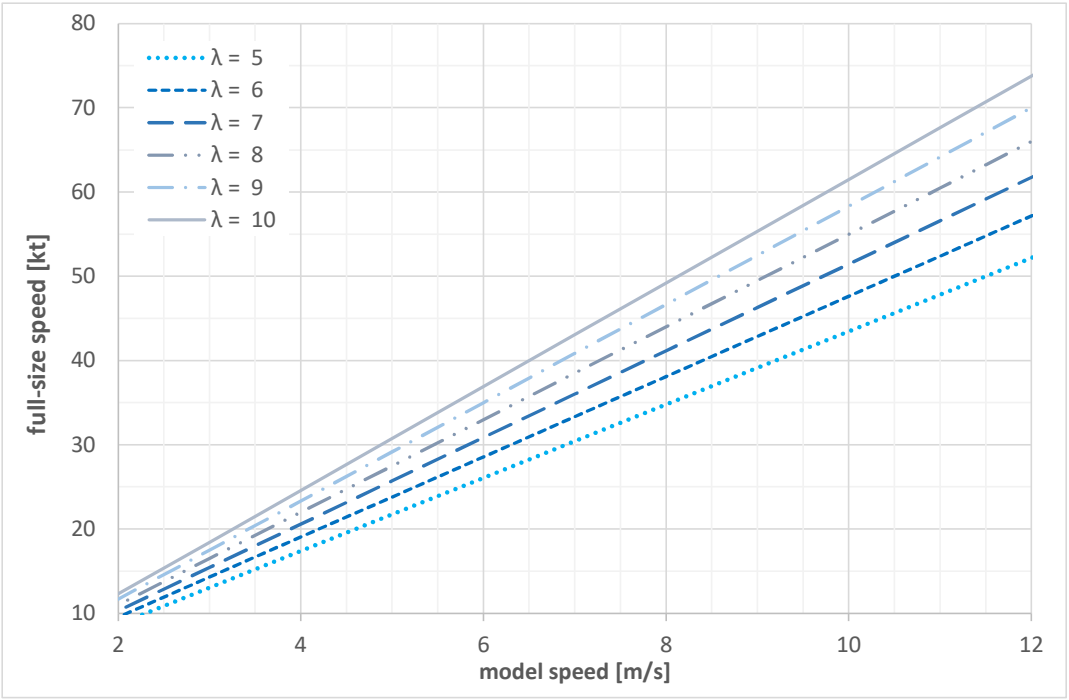


Figure 2-3 Full-size equivalent speeds for various scale factors

2.1.4 Model Testing

Once the lines were developed and model scale determined, a model-scale foam plug was cut of the moulded shape, controlled by a Computer-Aided Design (CAD) file sent to a multi-axis milling machine. The plug was then used as a former for a shell of Glass Reinforced Polyester (GRP); hand laid, vacuum bagged, and resin infused. The laminate schedule consisted of 2-4 plies (dependent on location) of E-glass, 300 gsm in a 2/2 twill weave. West System epoxy resin was used for the infusion.

Before lamination, a steel mounting plate was recessed into the deck amidships, bonded in and glassed over. This plate was tapped to mate with the threads from the mounting bolts on the towing rig.

A test rig was also designed and constructed to allow the hull to be mounted and positioned as desired for the test schedule. The model would be constrained in all degrees of freedom in order to measure the pure hydrodynamic loads at each given height and angle. The rig therefore had to allow for vertical positioning (heave control) and longitudinal trimming (pitch control). These adjustments had to be made from above the water, i.e. from the towing carriage, to avoid having to take the model out of the tank for every reposition, which would result in excessive down time between runs and increased likelihood of positioning errors.

By adjusting from a common starting position, the effect of each movement relative to the initial position was maintained. The layout of the towing carriage at the test facility was used to locate two horizontal main support I-beams that the two vertical adjustment struts bolted to.

The loads were measured by an ATI Omega160 6-component force/torque transducer IP68-rated, with the data acquired through vendor-supplied software and output to an excel file for storage and analysis. The transducer was mounted above the water surface, between the model and the rigid plate holding the fore and aft adjustment struts.

Calibration of the transducer consisted of setting up known weights prior to installation on the rig, to ensure measurement accuracy and sense direction of the output.

The testing programme matrix included four displacement conditions (with corresponding heights above datum) and two trim angles: 0° and 3° bow up. Speed runs were to be carried out between 1 m/s and 12 m/s to assess the conditions that would most likely be seen by each of the combinations. Seven configurations would be tested in total, four in the even keel condition and three at 3° trim.

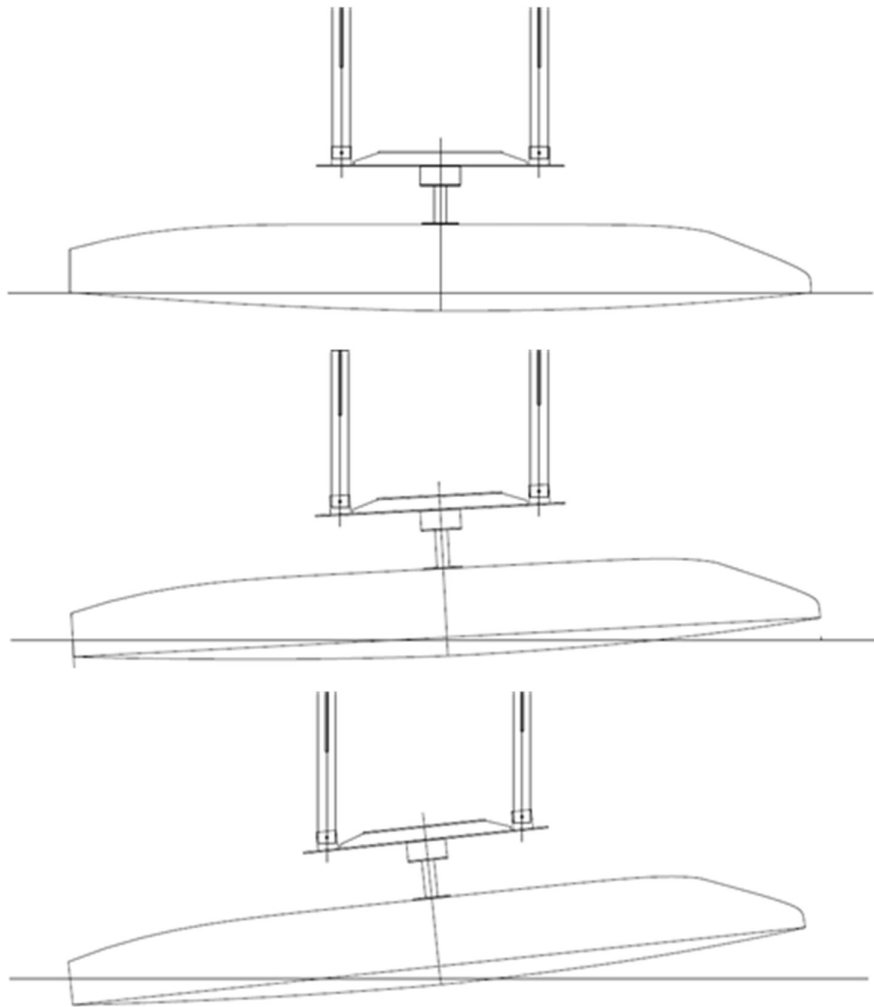


Figure 2-4 Diagram of model on test rig at trims of 0° , 3° and 6° (from top to bottom) corresponding to equal displacements



Figure 2-5 Process of the model lamination: from top, bare foam plug, inverted and wrapped in glass fibre, then vacuum bagged during the resin infusion process. The line of advancing resin can be seen toward the stern

2.1.5 Test Facility

As described in Section 2.1.3, it was necessary to find a tank testing facility with carriage speed up to 12 m/s to meet the 70 kt scaled equivalent speed. This is considerably faster than what is found in typical facilities but one site in the UK was found to be suitable, the ex-MoD site at Qinetiq-Haslar, near Gosport.

The tests were undertaken in April 2014, with the support and assistance of the on-site staff. The model was set up under the carriage and data acquisition sensors and software were calibrated. A sampling frequency of 100 Hz was selected to satisfactorily capture potential periodic wave phenomena while not resolving spurious high frequency vibration due to rail contact or other tank effects. The tank possessed wavemaking capabilities but this was not required for the initial round of testing.

Runs were carried out up to the maximum towing speed, and accelerations/decelerations up to 1 m/s². Table 2-2 lists the primary tank dimensions and specifications.

Photographs showing the adjustment rig and sensor arrangement installed on the model under the carriage are presented in Figure 2-6.

Table 2-2 Primary dimensions and specifications for Haslar towing tank

<i>property</i>	<i>unit</i>	<i>value</i>
Tank Length	m	270
Tank Width	m	12.2
Water Depth	m	5.4
Maximum Carriage Speed	m/s	12.75
Maximum Acceleration	m/s ²	1.1
Maximum Drag Load	kN	5.0

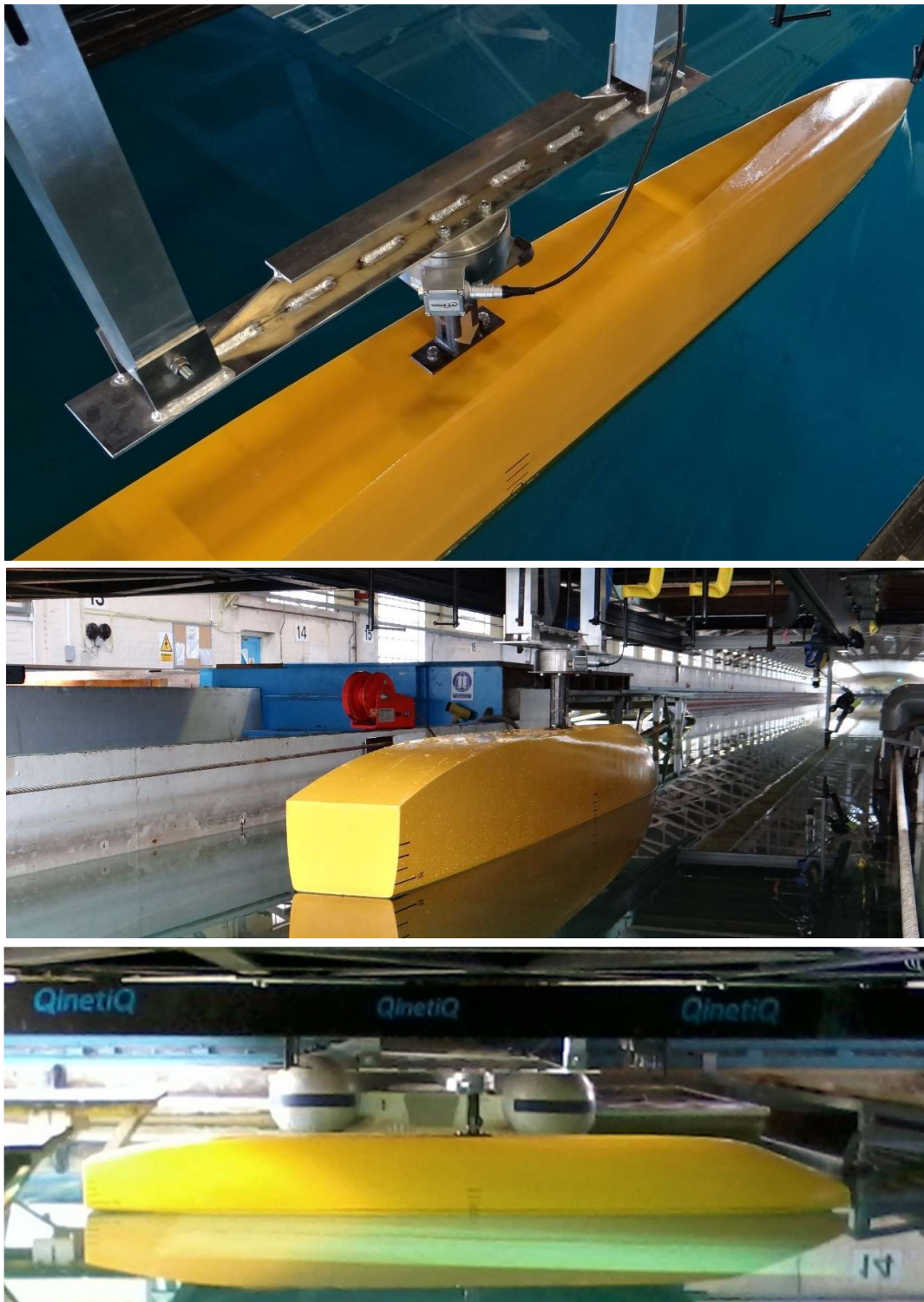


Figure 2-6 Photos of model setup in tank, carriage attachment with sensor (top), model mounted under carriage (middle & bottom)

2.2 Database of Aerodynamic Coefficients

This section documents the methodology used to numerically analyse the performance of several airfoil profiles IGE. The validity of the computational model was established through referencing available GE data for a known profile, so that subsequent profiles could then be analysed reliably.

All GE vehicles require inherent stability in the vertical direction to avoid constant correction to the ground clearance. In WIG craft, the total lift force generated is a function of both Angle of Attack (AoA) and height. In the general case, lift force increases as ground clearance is reduced. Stability is achieved when a decrease in height results in an increase of lift, or equally that an increase in height results in a decrease of lift, restoring the craft to the original height.

In order to quantify the force and moment changes that occur as a profile approaches the ground, several airfoil profiles were to be modelled using a Computational Fluid Dynamics (CFD) code. The derived quantities of lift, drag and moment over a range of operational angles of attack (α) and heights above ground, normalised to chord length ($h/c = \bar{h}$), have been determined. The CFD programme of work began simply, investigating the two-dimensional sectional characteristics, using a fully viscous method in a commercial solver.

Potential flow codes have been widely used to assess aerodynamic flow fields for decades and are known to provide solutions of good accuracy in these conditions. However, the velocity distributions obtained by means of a stream function and a velocity potential do not satisfy the no-slip condition at a solid boundary. Therefore, potential flow solutions are of no value in describing transport phenomena in the vicinity of a wall or solid surface (Bird, Stewart and Lightfoot, 2002).

Consequently, the decision to utilise a viscous method was considered to be essential for this analysis. Although inviscid theory adequately predicts pressure distributions and lift forces for typical airfoils in freestream conditions, accurately capturing the interaction of the boundary layers on the airfoil surfaces and ground plane is of utmost importance, especially as the distance between the two is reduced to the EGE zone.

A relatively simple profile with published performance data was selected for initial mesh setup and validation. The NACA 4412 cambered airfoil was chosen as this is one of the few profiles that has been compared experimentally and numerically, both in ground effect and in unbounded flow, with published results in the public domain. Additionally, this profile utilises an almost flat lower surface, which appears to be beneficial IGE where a Venturi effect can be set up under a surface with greater curvature, such as that found on a symmetrical NACA section.

It was found that much less information has been published regarding computational analysis or experimental testing of airfoils in ground effect when compared to unbounded flow conditions, even though the presence of the ground surface greatly influences the domain extents, mesh configuration and selection of boundary conditions. Furthermore, reference values for GE conditions were not straightforward, with experimental results varying significantly from one study to another, even showing trends that are opposite to known empirical and experimental evidence.

2.2.1 Modelling Approach

The modelling approach for the airfoil profiles was decided to be within a two-dimensional domain to capture the aerodynamic sectional characteristics, utilising the Reynolds-Averaged Navier-Stokes (RANS) equations, which approximate real-world three-dimensional unsteady flow with averaged, steady state solutions.

The numerical values of flow variables, such as velocities and pressures, are obtained by solving a system of governing equations composed of the continuity (conservation of mass), momentum (equations of motion) and energy (conservation of energy) equations.

The flow regime is considered low speed, where $Ma < 0.3$, so density variations due to pressure have been neglected resulting in an incompressible fluid approximation, i.e. constant density within any infinitesimal fluid element, with constant viscosity.

2.2.1.1 RANS Approximation

The underlying assumption of Reynolds averaging is that the time-variant turbulence can be approximated by decomposition into an averaged value and a fluctuating value. This can be represented as:

$$u(x, t) = \bar{u}(x) + u'(x, t) \quad (2-1)$$

where $\bar{u}(x)$ is the mean and $u'(x, t)$ is the fluctuating part

By definition, the average of the fluctuations is zero ($\bar{u'} = 0$) whilst averaging an average returns the same value ($\bar{\bar{u}} = \bar{u}$). Therefore, when $u(x, t)$ is substituted into the continuity equation:

$$\nabla \cdot U = \nabla \cdot (\bar{U} + U') \rightarrow \nabla \cdot \bar{U} = \nabla \cdot \bar{U'} \rightarrow \nabla \cdot \bar{U'} = \nabla \cdot \bar{U} = 0 \quad (2-2)$$

The conservation laws together with assumptions for shear stresses and equations of state represent a closed system. The computational code is then used for the numerical solution of this system. By considering the flow incompressible, the local pressures cannot be linked to variations in density. If the pressures are known, momentum can be found but there is then no direct way to determine the new pressures. These decoupling problems are typically resolved using iterative methods for the solution of the pressure and velocity fields.

The cases being studied would simulate wall-bounded flow, whereby although turbulent, the flow remains attached to the airfoil surfaces along most of the length. Viscous effects become important near the boundaries, and in other areas where a significant change of the flow-field solution would be expected. Vorticity is generated when the freestream flow is impeded by the no-slip boundary condition imposed upon the airfoil surface. These vortices can then propagate outward from the surface normal, upstream into the previously freestream flow and downward towards the simulated ground boundary. As any stationary wall boundary condition requires zero tangential flow velocity on the surface, there exists necessarily a velocity profile in the boundary layer that can be given as a function of distance from the wall. The region between the airfoil and ground is of particular importance for GE modelling, due to the interaction of the boundary layer

flows, especially in EGE, and the resulting contribution of the reduced-velocity, over-pressure zone to the generation of increased lift. Figure 2-7 shows three permutations of velocity profiles that would occur around the airfoil, with the adverse pressure gradient at the wall of particular significance.

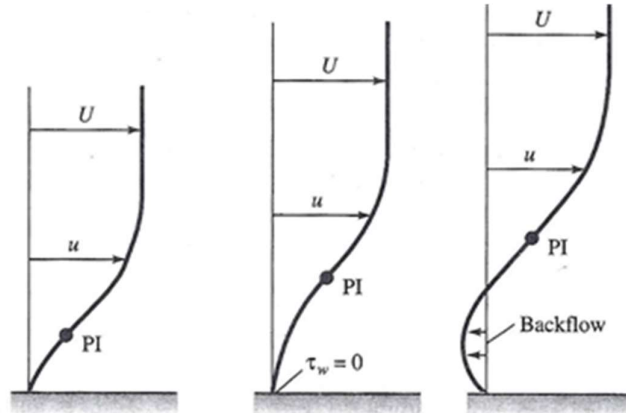


Figure 2-7 Diagram of three pressure gradients of boundary layer velocity profiles; from left, weak adverse gradient, critical adverse gradient, and excessive adverse gradient. Note PI = point of inflection (White, 2011)

To solve the RANS equations, the commercial finite volume code ANSYS FLUENT 14.5 was used, specifically the steady-state, pressure-based, semi-implicit (SIMPLE) solver. Second-order Taylor series expansion upwind schemes were used for the cell-face interpolation of the momentum equations, turbulent kinetic energy and specific dissipation rate. This is equivalent to a linear interpolation, where the gradient in the cell centre is used to evaluate the velocity normal to the cell face.

For the pressure-correction iterative methods used to solve the decoupled pressure and velocity field equations, the change of value for each variable from one iteration to the next (i.e. solution convergence) were adjusted via Under-Relaxation Factors (URFs). The URFs affect convergence of the numerical scheme, whereby stability of solution, especially in cases of turbulent flow, may be dependent on selection of URFs within an appropriate range (Barron and Salehi Neyshabouri, 2003). The dampening effect reduces oscillatory behaviour, and potential divergence, of the solution but also increases computational time; therefore, the URFs were kept as high as practicable. The URF that

was used for pressure convergence was typically 0.25 – 0.30 and for momentum in the range of 0.6 – 0.7. The specific URF values for turbulent kinetic energy, specific dissipation rate, and turbulent viscosity were left at the default settings, as recommended for external aerodynamic flows, given as 0.8, 0.8, and 1.0, respectively.

2.2.1.2 Turbulence Model

Due to the intended application of an external aerodynamic flow with a freestream velocity of approximately 100 kt over the full-size vehicle, with an averaged chord length around 20 m, the computational approach was to assume fully turbulent flow modelling, i.e. assumption of a fully turbulent boundary layer along the streamwise direction. The modelling was not intended to locate the distance where laminar-turbulent transition would be expected, nor the investigation of stall separation at high angles of attack, due to the expected operating profile of the vehicle.

A relatively high Reynolds number of 10^6 was specified for the free stream velocity; although this is lower than the anticipated full-size flow conditions based on characteristic length, only very small differences would be expected when compared to a fully turbulent flow regime. This difference would be mainly due to additional pressure in the boundary layer being imposed on it by the external flow, with a very small pressure gradient across the boundary layer for large Reynolds numbers.

As the RANS equations are not a closed set, it is not possible to solve for the Reynolds stresses directly; however, several turbulence models have been developed for external aerodynamic applications, with two of the most widely used being the k - ε and k - ω models. The ω -equation formulation offers several important advantages over the ε -equation, most notably that it can be integrated through the viscous sublayer without requiring inclusion of any additional terms, and that it has been shown to be better at predicting adverse pressure gradient boundary layer flows including separation behaviour. These advantages make the k - ω model ideal for airfoil applications. However, the ω -equation is highly sensitive to freestream values of k and ω outside of the shear layer, where the ε -equation has been shown to be more accurate.

A quantitative study of six turbulence models popularly used for external aerodynamic flows has shown that ground effect surface pressures were most accurately predicted with

the SST $k-\omega$ model over all heights, and especially at lower heights with larger pressure gradients (Mahon and Zhang, 2005). These turbulence models were all single and two-equation linear eddy-viscosity models, which included Spalart-Allmaras (S-A), standard $k-\epsilon$, standard $k-\omega$, SST $k-\omega$, $k-\epsilon$ RNG, and Realisable $k-\epsilon$, with enhanced wall treatments used for all $k-\epsilon$ variants. Therefore, the turbulence model selected for this study was the two-equation Shear Stress Transport $k-\omega$ model (SST $k-\omega$), which is based on the original $k-\omega$ model but also accounts for the transport of the principal shear stress in adverse pressure gradient boundary layers (Menter, 1992).

The SST $k-\omega$ model was developed to blend the standard $k-\omega$ model, which is known to be robust and accurate in the near-wall region, with the $k-\epsilon$ model, known for accuracy in the free stream or far-field region. A blending function is used to increase the influence of the $k-\omega$ formulation near the wall, which then reduces to zero as the distance normal to the surface increases, leaving only the $k-\epsilon$ model. This combined method proves more accurate and reliable for adverse pressure gradient flows, such as airfoils, than the standard $k-\omega$ model (ANSYS, 2009).

For external flows, the freestream turbulent viscosity is typically on the order of the laminar viscosity. The ratio between these two values can be specified using a Turbulent Viscosity Ratio (TVR) at the inlet, defined as the ratio of turbulent dynamic viscosity to molecular dynamic viscosity, μ_T/μ . The value of μ_T relates the turbulent stresses to the averaged velocity gradients in the RANS equations. Specification of inlet TVR was selected as the best approach, as alternative ways of specifying turbulence conditions, e.g. the turbulent length scale, presented greater uncertainty. Suitable values of inlet TVR are not clearly defined but guidelines indicate that the value should be small; the range of 0.1 – 1.0 should be appropriate (ANSYS, 2011). The TVR was varied several orders of magnitude to gauge the sensitivity of the solution, from values of 0.1 to 10; however, the effect on the lift, drag and moment results was negligible.

2.2.1.3 Boundary Layer Resolution

In order to accurately resolve the boundary layer characteristics for the selected turbulence model, it was necessary to locate cell nodes inside the linear sublayer, where viscous stresses dominate and the Reynolds stress term is negligible. Moving away from

the near-wall linear region, Reynolds stress increases until viscous stress becomes negligible in the inertial sublayer. The near-wall localised velocities are required to estimate wall shear stress and corresponding viscous drag.

Therefore, the initial constraint on mesh setup was determination of an appropriate first cell layer height, as measured normal to the boundary of the profile surface, the distance commonly known as y-plus.

As a Reynolds number based on characteristic length (mean chord) would be meaningless in the near-wall region, where the fluid velocity decreases to zero at the wall boundary, an alternative method is required for determining boundary layer flow characteristics for a given velocity.

Estimation of the local skin friction coefficient in turbulent flow was given by the Schlichting skin-friction correlation line (Schlichting and Gersten, 2000):

$$Cf = [2 \log_{10} (Re_x) - 0.65]^{-2.3} \quad \text{for } Re_x < 10^9 \quad (2-3)$$

Wall shear stress (equation (2-4) and the defining equation for the viscosity of a Newtonian fluid as the wall normal distance tends to zero:

$$\tau_w = \frac{1}{2} \rho U_\infty^2 Cf \quad \tau_w = \mu \left(\frac{\partial u}{\partial y} \right)_{y=0} \quad (2-4), (2-5)$$

where μ is the dynamic viscosity of the fluid, u is the velocity in the principal direction of the flow, y is the cross-stream coordinate

Frictional, or wall shear, velocity is known as u^* is given in equation (2-6), leading to the determination of the dimensionless first layer distance from wall, y^+ , as given in the following equation:

$$u_* = \sqrt{\frac{\tau_w}{\rho}} \quad y^+ = \frac{u_* y}{\nu} \quad (2-6), (2-7)$$

The relevant parameters used for the calculation of the required first layer heights around the airfoil surfaces are given in Table 2-3.

Table 2-3 Parameters used for the first layer height calculation

	<i>symbol</i>	<i>value</i>	<i>unit</i>
length of boundary layer	L	1.00	m/s
velocity, free stream	U_{∞}	1.00	m/s
density	ρ	1.000	kg/m ³
dynamic viscosity	μ	1.00E-06	kg/ms
y+ target	y^+	3	
Re		1.00E+06	
kinematic viscosity	ν	1.00E-06	m ² /s
coefficient of skin friction	Cf	0.003745	
wall shear stress	τ_w	0.00187	N/m ²
friction velocity	u^*	0.04328	m/s
first layer height	Δy	0.00007	m

2.2.1.4 Boundary Conditions

A moving ground condition is required to accurately capture the physical flow field around a GE airfoil. A stationary ground results in excessively thick ground boundary layers and spurious high pressure regions of recirculation at the forward end of the lower surface, leading to resultant lift forces that actually reduce as the ground is approached (Hsiun and Chen, 1996; Firooz and Gadami, 2006). The ground plane boundary condition was specified as a moving surface with absolute velocity equal to U_{∞} , normalised to 1 m/s.

The following inlet/outlet flow boundaries were identified as appropriate for low-speed flows:

- Velocity inlet: upwind definition of the velocity and scalar properties of the flow at the inlet boundaries, in this case defined as 1 m/s.

- Pressure outlet: downwind definition of the static pressure and other scalar variables in the case of backflow at the outlet, e.g. TVR, in this case defined as zero gauge pressure.

The wall boundary on the upper side of the domain could be defined in a number of ways, as the intention was to ensure this boundary was sufficiently far from the area of interest to negate its effect on the solution. A slip condition was specified, but a symmetry condition produced no noticeable change in solution.

2.2.1.5 Grid Generation

The discretisation of the computational domain is achieved through placing nodes and conjoining cells throughout domain, resulting in a mesh or grid of nodes and cells that should capture flow features and geometry accurately. The number of nodes was increased in the flow regions where a significant variation of flow characteristics was expected, specifically around the airfoil surfaces and on the ground in the vicinity of the airfoil above. Conversely, the number of nodes were gradually reduced towards the areas where little change was expected from adjacent cells, i.e. in the far-field away from specific flow features of interest.

There are two fundamental classes of grid topologies used for the numerical solution of boundary value problems, each with their own advantages and disadvantages for use in this application: structured and unstructured (Liseiken, 1999):

- Structured grids have traditionally been favoured as they can be solved quickly, with high accuracy and good control over the topology. Multiple blocks can be used to grid complex geometries, with blocks fitted to match the modelled geometry.
- Unstructured grids offer the advantage of irregular connectivity and are therefore utilised in automatic grid generation methods. These can be useful for meshing complex geometries, where body-fitted structured grids may prove difficult. However, the unstructured nature leads to a limited amount of control over each parameter of the grid. Additionally, unstructured grids utilise less efficient solvers and can result in increased computational expense for a given solution.

Irrespective of the gridding strategy, errors in the numerical solutions will be minimised by maintaining certain characteristics in each of the computational volumes (grid cells). The accuracy of the simulation depends on the quality of the cells which should ideally be equilateral, with skewness and deformation minimised, and orthogonal near boundaries, *viz.* airfoil surfaces and ground plane. Stretching factors, or cell aspect ratios, higher than 20 to 100 in important regions of the flow domain and null-volume singularities should be avoided (ERCOFTAC, 2000). The topology of the grid should follow the geometry and anticipated flow streamlines as closely as practicable, ideally with orthogonal grid lines throughout.

To achieve these criteria, a structured mesh approach was adopted as there were several important benefits over a more automated, unstructured method. These benefits included:

- More repeatable mesh blocking structures around the airfoil and near the ground, with improved similarity of meshes between the various height and angle configurations and different profiles.
- More controllable, quad-only meshes with specific parameter definitions driving the refinement regions, leading to increased reliability of mesh quality.
- Increased modularity for scripting and batch operations, required to run the many configurations efficiently.

ICEM CFD was used to set up the computational domain, as it was found to provide more precise control of blocking topologies and edge parameters than the Ansys Meshing module that is provided with the Workbench GUI. Fourteen discrete mesh topologies were attempted using the Workbench Meshing module, with variations on rectangular vs. curved inlet and upstream domain, blocking strategies, edge parameter specification, etc.

The resulting grids were not sufficiently uniform over the range of heights and angles to provide confidence that results would be comparable between different configurations and the unpredictable and non-repeatable grid geometries were deemed to pose too great a risk to produce unreliable solutions.

Therefore, a scripted routine was specially written to import the airfoil coordinates, locate the airfoil in the desired position and orientation with reference to the trailing edge, create

the computational domain and set boundary conditions. The blocking strategy utilised a C-mesh wrapped around the curved airfoil surface and standard rectangular blocks in the rest of the domain, resulting in an H-mesh. Specific cell height values required for the boundary layer resolution near the airfoil surfaces and ground plane were controlled through nodal locations given to the C-mesh edge parameters.

The ICEM script has been included in Appendix 8.6.

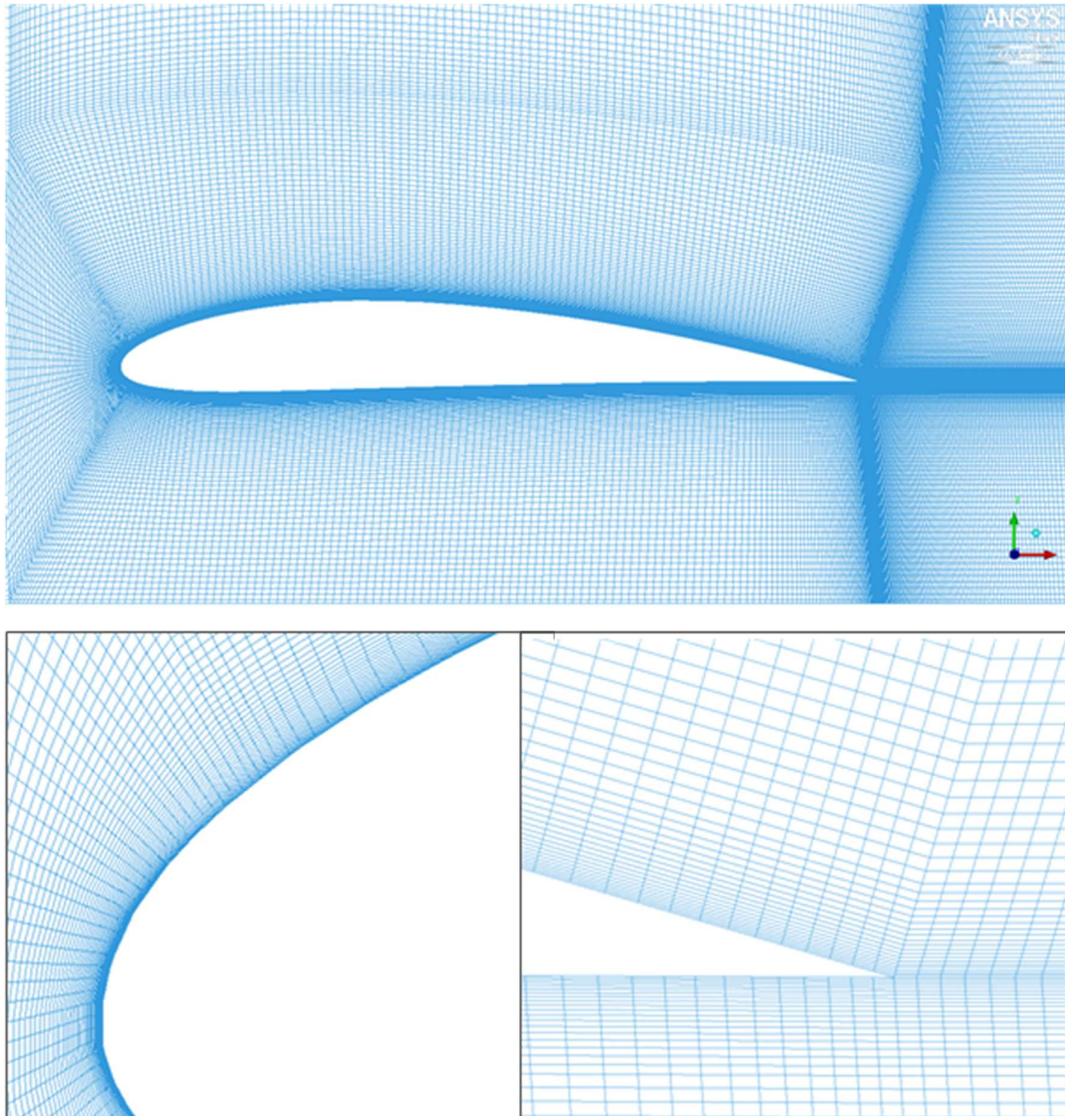


Figure 2-8 Mesh refinement in way of the airfoil, showing grid blocking at top, inflation layer at leading edge at bottom left, inflation layer at trailing edge at bottom right

2.2.1.6 Mesh Independence

Mesh independence was assessed by building meshes consisting of three sizes of computational domain and four mesh refinement levels. Due to boundary layer considerations (see section 2.2.1.3), the mesh in the immediate vicinity of the airfoil surfaces was varied only in the streamwise direction; the crossflow dimensions were determined by first layer height (y^+) requirements and inflation layer growth. The arithmetic mean of the cell dimensions for the streamwise coordinates around the airfoil and in the wake downstream is shown in Table 2-4, with values normalised against chord length.

Table 2-4 Averaged stream-wise cell sizes for varying mesh density

resolution	<i>airfoil surfaces</i>		<i>turbulent wake region</i>		
	no. of cells	$\overline{\Delta x}/c$	no. of cells	$\overline{\Delta x}/c$ (med)	$\overline{\Delta x}/c$ (lrg)
coarse	100	0.010	125	0.056	0.072
medium	150	0.007	250	0.028	0.036
fine	200	0.005	350	0.020	0.026
extra fine	250	0.004	450	0.016	0.020

The aim of the mesh independence analysis was to determine the substantive effects of grid parameters upon the force and moment outputs, which can be considered grid convergence. It was important for each of the test cases to achieve iterative convergence prior to any judgement about mesh quality, i.e. to ensure that the algebraic numerical scheme reached a stable and numerically accurate solution. Therefore, scaled residual criteria were set to 10^{-6} for continuity, x-velocity and y-velocity, and 10^{-5} for the kinetic energy and turbulent dissipation.

Monitors were created to read lift force (y-component), drag force (x-component) and pitching moment (about z-axis) using the airfoil trailing edge as the reference point. The pitching moment can later be transformed along the chord length to determine neutral points (the locations of constant moment) for pitch and height variations.

Unbounded flow simulations for typical airfoils should utilise a domain sufficiently large to ensure the effect of upwash generated by the lifting body does not reach the far-field boundary; therefore, these boundaries are recommended to extend 10 to 20 chord lengths ($10c - 20c$) around the airfoil (ERCOFTAC, 2000). Clearly, the distance to the boundary under the airfoil must be less than this recommendation to investigate the effect of the ground plane but it is not clear how this very-near wall affects the flow at the far-field.

Several numerical studies of GE airfoils have used computational domains that could be considered insufficiently small when judged by conventional aerodynamic standards. Published WIG research has reported that a much smaller domain, e.g. extending $3c$ upstream of the leading edge, $5c$ downstream of the trailing edge, and $4c$ above the upper surface, has produced acceptable results (Firooz and Gadami, 2006; Abramowski, 2007).

As the results given by these reduced-domain meshes have been reported as satisfactory, it appears that the presence of the ground plane stabilises the flow conditions around the airfoil to the extent that far-field effects become less significant. In order to assess this effect in greater detail, the mesh independence analysis included domain size as a variable.

A rectangular domain was used for three sizes, consisting of small, medium and large dimensions. The small size used the same chord-normalised distances as given in the referenced WIG reports (see preceding paragraphs), while the upwind and downwind dimensions were increased in increments of $2c$ and the upper boundary by $1c$ for the remaining two sizes. These dimensions are represented graphically in Figure 2-9.

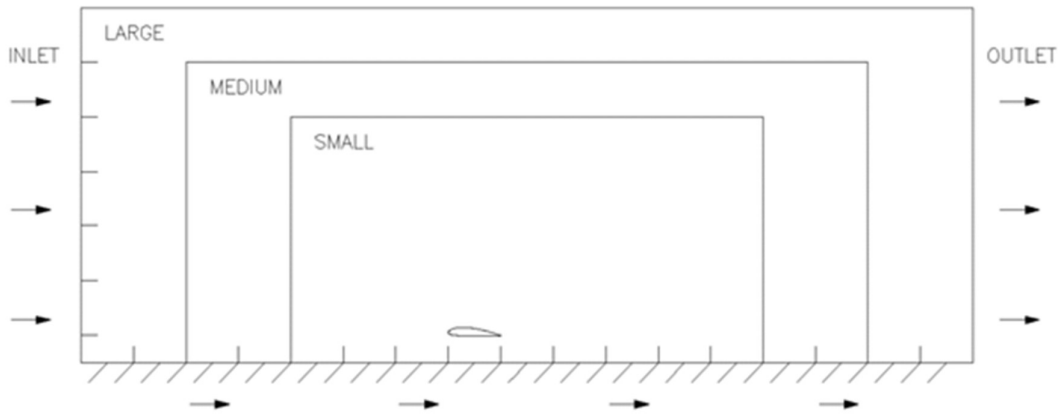


Figure 2-9 Illustration of the three domain sizes, with tick marks to indicate chord lengths

A NACA 4412 profile was selected for the independence analysis, at a moderate angle of attack, $\alpha = 4^\circ$, and moderate height, $\bar{h} = 0.4$. These values were chosen as they were close to the mid-range values for the parameters of interest for typical WIG operation.

The first three density resolutions showed lift, drag and moment values that were similar for the medium and large domains, with an average difference within 0.5%. The smallest domain returned values that showed a greater difference compared to the other two sizes. Therefore, it was decided to remove this size from further consideration. A fourth resolution was set up for the medium and large domains, to see if the solutions would converge further. Both domains exhibited similar slight increases in lift and moment, with decreases in drag.

The range of c_l and c_m values varied less than 0.2% from the coarse mesh to the extra-fine for the medium domain size, and slightly greater than 0.2% for the small and large domains. Drag values were within 2% for all resolutions of the small and medium domains, and under 3% for the largest domain.

In practice, it is likely that even the smallest domain with the coarsest mesh resulted in force and moment estimations that would be of sufficient accuracy for many engineering applications. However, in the present work, the medium-size domain with a density around 200 000 nodes was selected as the default configuration, offering the most suitable trade-off of accuracy versus computational expense.

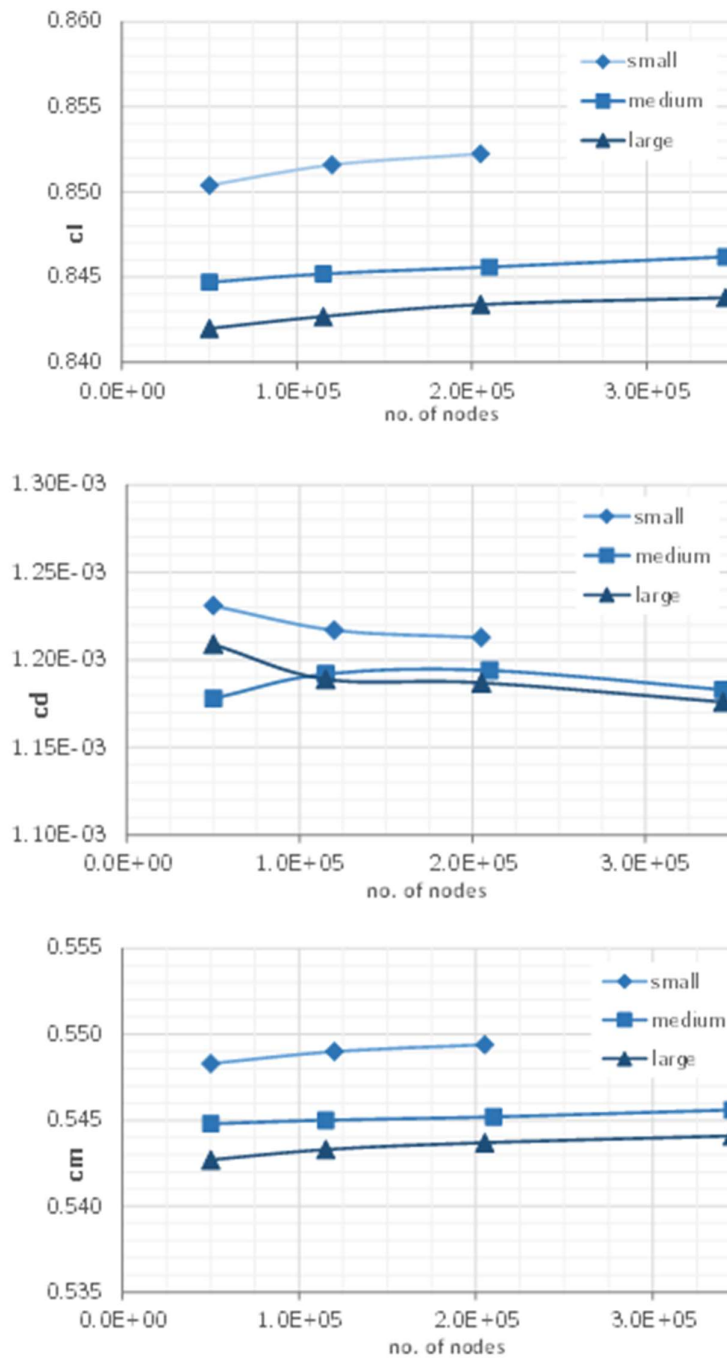


Figure 2-10 Plots of c_l , c_d and c_m (from top) for the three domain sizes with varying mesh density

2.2.2 Validation of CFD Results

The strategy of the validation procedure was to assess how accurately the computational results compared with experimental data. Validation was required in order to gain confidence that the computational results were accurately representative of the physical system.

2.2.2.1 Comparison to Experimental Results

It was found that much less information has been published regarding experimental testing of airfoils IGE compared to unbounded flow conditions, even though the presence of the ground surface greatly influences the pressure distribution and circulation around the airfoil, and thus lift, drag and moment characteristics.

A relatively simple profile with some published performance data was selected for initial mesh setup and validation. A NACA 4412 cambered airfoil was chosen as this is one of the few profiles that has been compared experimentally and numerically, both in ground effect and in unbounded flow, with published results in the public domain.

Ahmed, Takasaki and Kohama (2007) experimentally tested a NACA 4412 profile in a wind tunnel with moving ground, with particular emphasis on replicating two-dimensional flow. Lift and drag forces were measured, as well as the pressure distribution over the upper and lower surfaces of the airfoil. Endplate dimensions were carefully selected to replicate purely streamwise flow, not only restricting the formation of tip vortices that would cause an outward spanwise tendency, but also ensuring their presence did not introduce an inward spanwise component. The results of this work were initially used for comparison.

Lift is created when a pressure differential between the upper and lower surfaces of an airfoil occurs; therefore, comparison of pressure distributions is a more direct method of assessing the lift and moment characteristics of a given configuration. Local pressures are measured at specified points over the airfoil surfaces, then non-dimensionalised against the freestream pressure. This results in pressure coefficients (C_p) that are used to describe relative pressures in the flow field. Integration of the C_p profile yields the orthogonal lift and drag vectors.

Distributions of the local C_p as determined by CFD were compared to the experimental results as shown in Figure 2-11 and Figure 2-12. The plots show two angles, $\alpha = 4^\circ$ and $\alpha = 8^\circ$, respectively, and four discrete heights for each angle: $\bar{h} = 0.05$, $\bar{h} = 0.15$, $\bar{h} = 0.40$, and $\bar{h} = 1.0$. The left hand side of the figures are visualisations of the CFD-derived C_p , and the right hand side shows the comparison of CFD to experiment. The Reynolds numbers of the tested conditions were not exactly the same, with the experimental $Re = 3 \times 10^5$ and numerical $Re = 1 \times 10^6$. However, at normal angles of attack, i.e. before flow separation characteristic of the onset of stall, pressure distributions over a NACA 4412 are practically unaffected by Reynolds number over the range of $10^5 \leq Re \leq 8 \times 10^6$ (Pinkerton, 1938).

Qualitatively, the correlations appear quite good, especially for the heights furthest from the ground. At the lowest height, $\bar{h} = 0.05$, the CFD pressures on the lower surfaces are noticeably higher than those recorded by experiment for both angles. As the upper surface pressures calculated by CFD are slightly lower than experimentally measured, this indicates that CFD would over-predict upper to lower surface pressure differential when compared to experiment, which would result in greater predicted lift force.

In order to determine where the main differences between the two methods were occurring, local pressure differentials between upper and lower surfaces at each chordwise location were calculated for the experimental results and for the numerical results. These local C_p values were compared, normalised to the experimental results. Figure 2-13 illustrates the errors between experiment and CFD, where the positive ordinate values indicate greater pressure differentials calculated by CFD and negative indicates greater differentials measured by experiment.

It is clear that the largest discrepancies are found at the lowest heights, with CFD C_p values over 50% greater than experiment found towards the leading edge and trailing edge extremities. An outlying point near the trailing edge for $\alpha = 4^\circ$ shows the numerical C_p to be approaching double that measured experimentally, however this can be attributed to the overall smaller force magnitudes at this location.

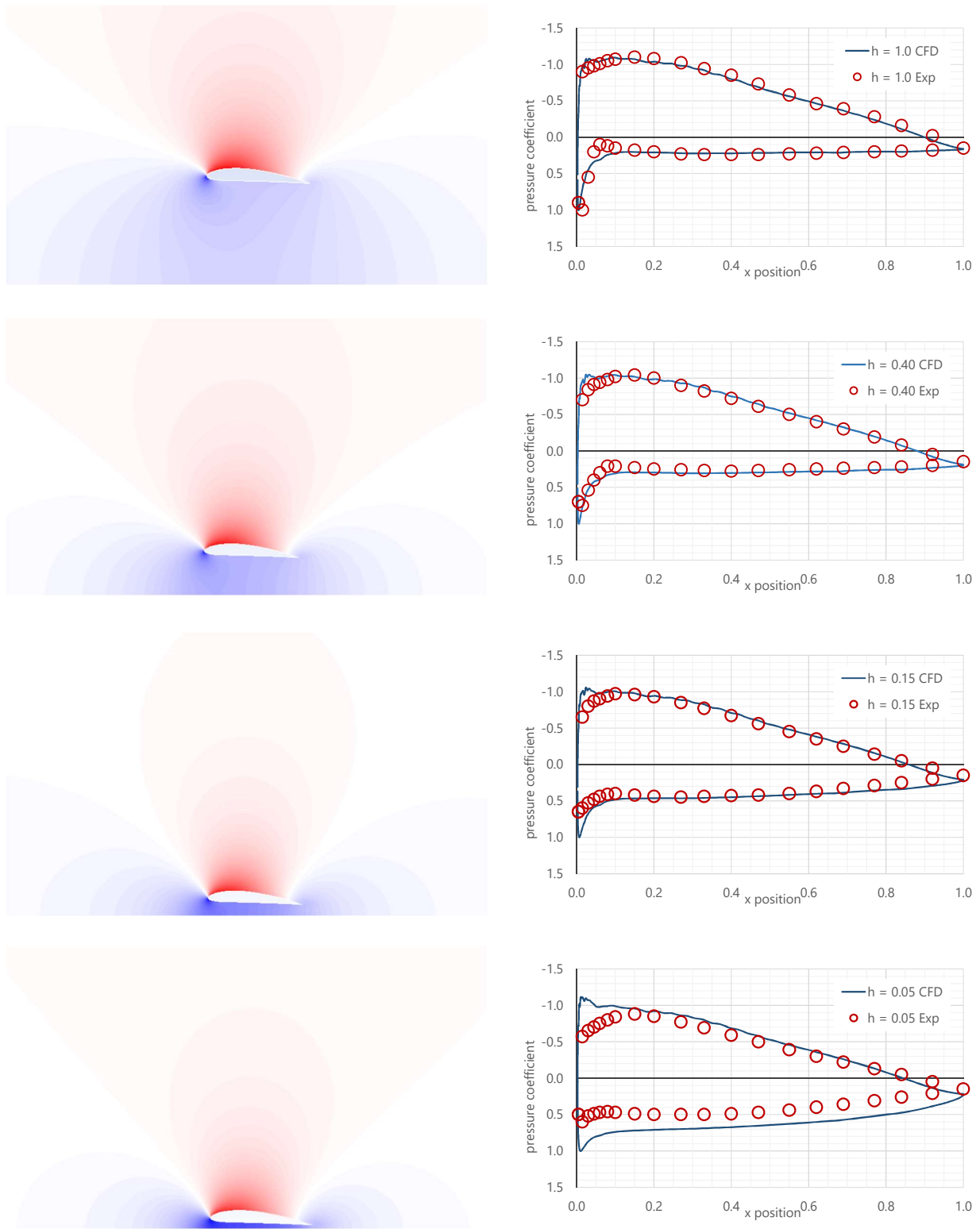


Figure 2-11 Pressure contours and profile distributions for a NACA 4412 at $\alpha=4^\circ$, with height $1.0 \geq \bar{h} \geq 0.05$ (from top)

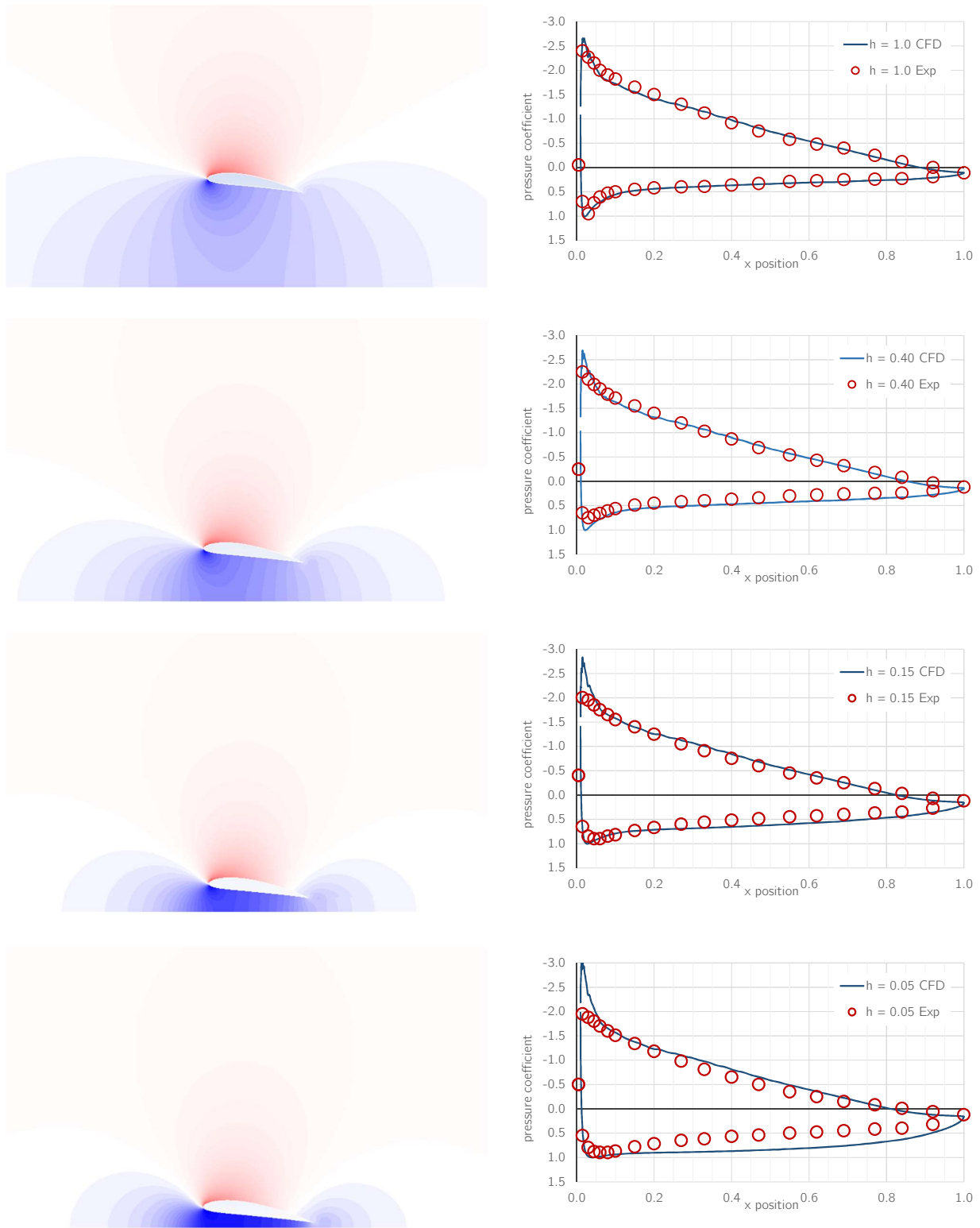


Figure 2-12 Pressure contours and profile distributions for a NACA 4412 at $\alpha=8^\circ$, with height $1.0 \geq \bar{h} \geq 0.05$ (from top)

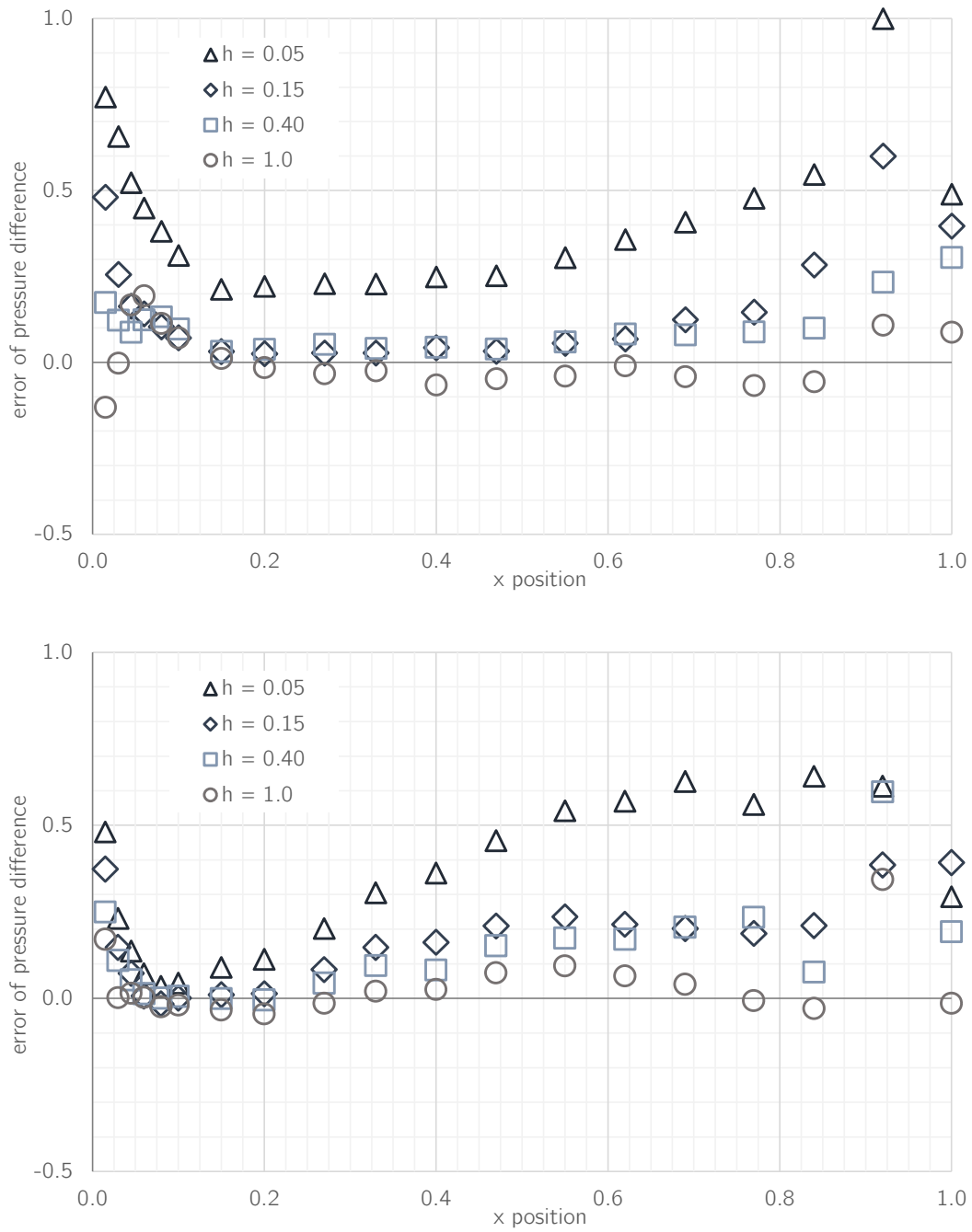


Figure 2-13 Plot of local C_p differences between CFD and experiment; 4° (top) & 8° (bottom)

As the accuracy of the experimental results was not known, additional analysis of the published data was carried out to investigate the source of these significant pressure differences. The overall lift force generated by a given configuration would be the sum of the local pressures integrated around the body, so the reported c_l values for each of the experimental configurations were compared.

Lift coefficients were reported for the corresponding C_p configurations by Ahmed; however, as the distance to the ground was reduced, the trend showed a decrease of lift for $\alpha = 4^\circ$ and a very minor increase of lift for $\alpha = 8^\circ$, results which are contrary to the concept of increased lift efficiency in the ground effect zone.

To verify the accuracy of these reported c_l results, the given C_p distributions were manually integrated using a simple trapezoidal method. The correlation of the reported values to the integrated values for the experimental results is shown in the upper plot of Figure 2-14. The differences between these values were found to be between 5% and 19%, with the manual method consistently producing lower resultant lift values.

For comparison, a similar integration method was applied to the C_p profiles obtained from the CFD models, using the c_l as given by the software as the reported values. The correlation with the CFD pressures was much more consistent than that from the experimental report for both angles of attack and across all heights, as shown in the lower plot of Figure 2-14. The differences were between 3% and 5%, with the manual method again lower in all cases. It is likely this small discrepancy is due to the coarseness of the trapezoidal integration.

It was concluded that there was not satisfactory agreement between the experimentally reported localised pressures and overall lift force. Although the manual integration technique produced slightly lower c_l for the CFD pressures, the difference was much smaller and much more consistent.

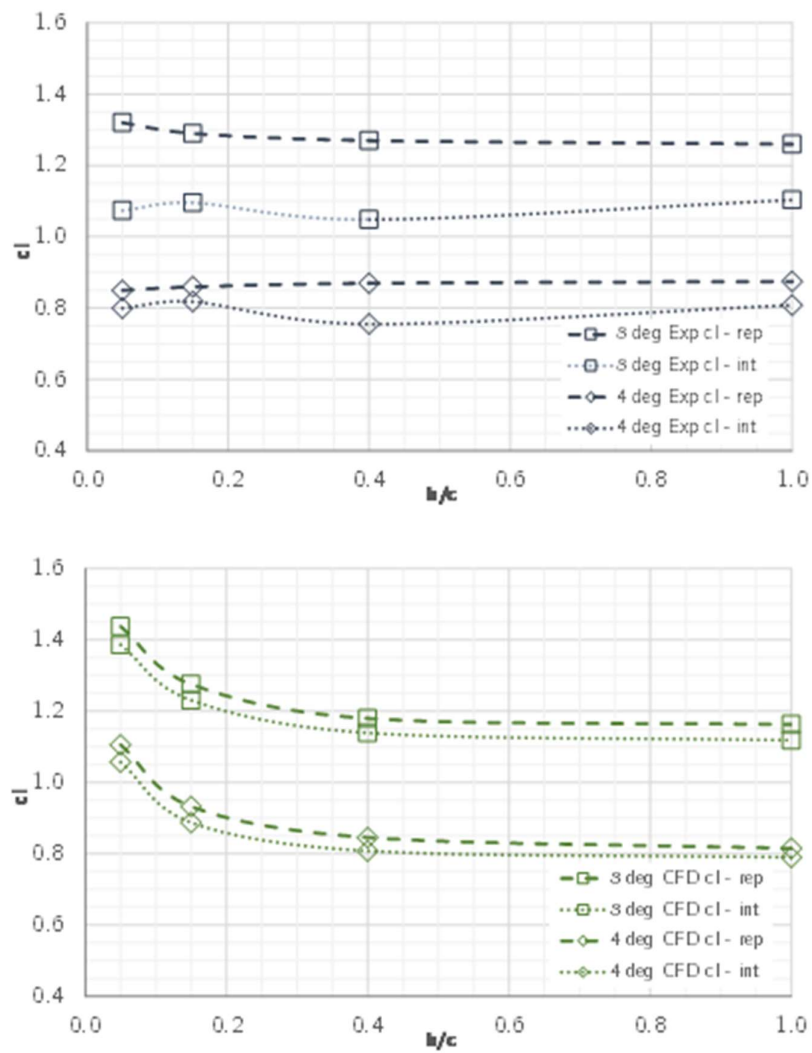


Figure 2-14 Reported values of c_l compared to integration of pressure distributions, for experimental results (upper) and CFD (lower)

2.2.2.2 Comparison to Numerical Results

As the experimental pressure and lift values were shown to be somewhat unreliable, it was necessary to directly compare the c_l results from CFD with additional published values from both experiment and numerical studies.

Ockfen and Matveev (2009) performed a 2D RANS study of the NACA 4412 in EGE and heights up to $\bar{h} = 0.8$ at $Re = 8.2 \times 10^6$. Finite volume CFD was used with the S-A turbulence model. It was reported that the predicted lift and moment values agreed with experimental results for moderate AoA. The experimental results in question were those published by Kikuchi et al. (2002), who investigated the ground effect performance of a NACA 4412 profile while towed in an outdoor guideway of a MagLev test facility, for use on an Aerotrain concept flying in an open channel. Lift coefficients were supplied for what was described as $\alpha = 6^\circ$, although when plotted alongside the results from other researchers, the values appear to approximate an $\alpha = 5^\circ$ line. Interestingly, as the GE influence reduces, these values appear to converge with the experimental $\alpha = 4^\circ$ line of Ahmed, et al., as seen in Figure 2-15.

Additionally, Barber et al (1998) analysed the NACA 4412 at $\alpha = 4^\circ$ using the CFD code CFX4 to compare lift and drag coefficients IGE with varying ground boundary conditions for usage with numerical methods. They concluded that the most realistic condition is a solid no-slip surface that moves horizontally with the same velocity as the free stream. In contrast, the no-slip boundary with zero horizontal velocity should be avoided as the effect of the boundary layer formation gives inaccurate results. Their results show a clear reduction in c_l at ground clearances below $\bar{h} = 0.2$, which may account for the anomalous experimental results discussed in the previous section. Their numerical results with appropriate boundary conditions are included in Figure 2-15. While the trend follows many of the other results, the magnitude appears over-predicted. Ockfen and Matveev also disagree on the magnitude of the predicted forces IGE of this work.

Firooz and Gadami (2006) numerically investigated the NACA 4412 in the GE zone, with emphasis on the comparison of fixed and moving ground, under two selected turbulence models, the Realisable k- ϵ with enhanced wall treatment and S-A. There was not a significant difference in the lift forces resulting from the different turbulence models. Their reported results covered $4^\circ \leq \alpha \leq 8^\circ$ for the fixed and moving ground conditions,

again reporting a clear loss of lift near the ground for the fixed condition. Their lift results for $\alpha = 4^\circ$ are very similar to those reported by Barber et al, and have therefore not been overlaid onto the figure.

Smith et al (2008) conducted a computational analysis of two airfoil profiles IGE: a NACA 4412 and Wortmann FX 63-137. An interesting feature of this analysis was that a laminar flow regime was enforced over the airfoil, even though the freestream $Re = 3 \times 10^5$ indicated a transitional flow regime. This was done in an attempt to avoid the over-prediction of drag that is caused by implementing a turbulence model along the entire length of an airfoil; as the flow regime would not be expected to be fully turbulent at this Re , there should be a laminar to turbulent transition point, with lower skin friction upwind of this point.

It is interesting to note that the results of Ockfen and Matveev, Barber et al, and Firooz and Gadami all report c_l somewhat higher than expected; the first two studies were run at $Re = 8.2 \times 10^6$ and the latter at $Re = 2 \times 10^6$. The free stream c_l is plotted for experimental results at $Re = 3 \times 10^6$ and increases slightly up to approximately $c_l = 0.85$ at $Re = 9 \times 10^6$ (Abbott and Von Doenhoff, 1959). Hsiun and Chen (1996) report a small but steady increase in c_l for $\alpha = 5^\circ$ over the range $0.5 \times 10^6 \leq Re \leq 2.0 \times 10^6$, so this trend may continue rising with increasing c_l .

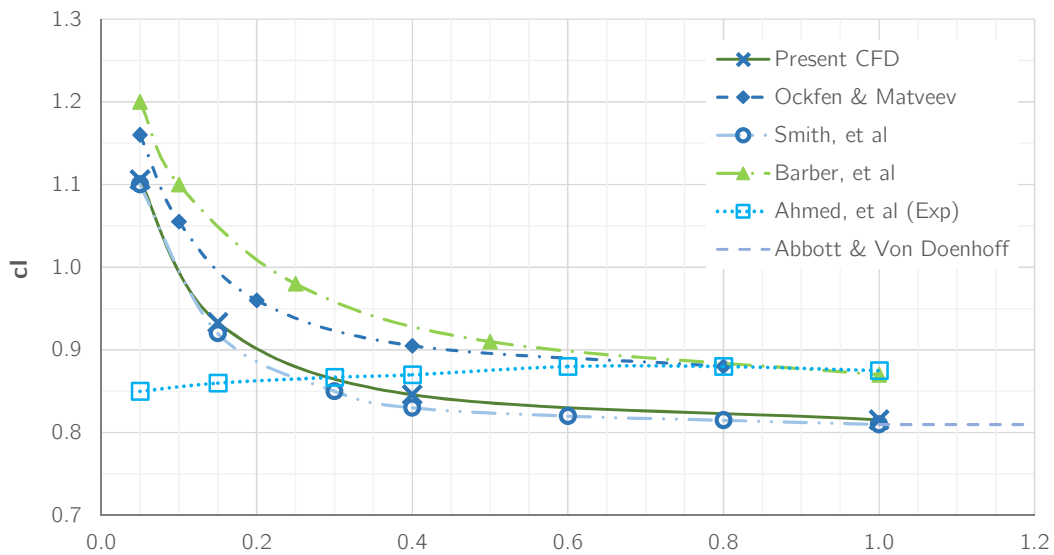


Figure 2-15 Lift coefficient comparison of numerical and experimental reports of a NACA 4412 at $\alpha = 4^\circ$

It can be seen that the experimental results of Ahmed et al (2007) do not correspond to the findings of the other researchers. The increased lift in the GEZ appears to be entirely missing, as lift is shown to actually decrease. Furthermore, the reported drag values increase in this region, leading to a lower L/D, i.e. lower aerodynamic efficiency. This result is not in accordance with empirical evidence regarding effects on lift and drag IGE.

Possible reasons for this experimental result include using a moving belt that did not extend across the entire span of the airfoil, or that a boundary layer was allowed to build up on the ground surface that would then interact with the boundary layer produced on the airfoil surfaces. It is the interaction of the flow over the airfoil with the ground boundary layer that causes a reduction of the lifting force. The experimental results would be consistent with either of these conditions.

It has long been established that lift will be reduced and drag will increase if an airfoil is placed in a moving fluid over a stationary ground. Raymond (1921) declared the results obtained from a fixed-ground wind tunnel experiment as ‘not entirely satisfactory’, the fact that ground plate was stationary with respect to the airfoil being the primary fault, with other methods (e.g. reflection method, placing an identical airfoil inverted in a free stream at a distance of $2\bar{h}$) giving results of more practical value.

Hsiun and Chen (1996) conducted a numerical study using viscous, incompressible N-S equations with a stationary ground condition. They showed a small increase in lift as height decreased, until around $h/c = 0.25$, where a marked and rapid decrease in lift was observed. A region of flow recirculation due to viscous effects was demonstrated between the leading edge and the ground at very small heights, affecting the pressure distribution over the lower surface. This change in the flow field resulted in a reduction in pressure differential between the upper and lower surface, leading to reduced lift. Interestingly, drag is also shown to decrease with height, although others have reported increased drag with this ground condition.

The experimental results do not demonstrate this marked reduction solely in the EGE zone, so it may not be that a ground boundary layer interaction is the primary cause of the unexpected lift reduction. However, these seemingly anomalous results were not commented upon in the report of that work and the cause remains unknown.

2.3 Experimental Technique for GE Testing

As reliable experimental test results of airfoils IGE have proven to be in short supply, it was decided to conduct a series of physical model tests in the Ocean Systems Test Laboratory at Cranfield University, where it would be possible to more directly replicate the physics of a moving wing through a stationary fluid, over a stationary ground, using a towing tank filled with fresh water.

Water would be used as the working medium, substituted for air in the full-size application, with the solid tank bottom representing the water surface. Differences in density and kinematic viscosity between air and water would allow the towed velocity to be much lower than the airspeed required in a standard wind tunnel for a given Reynolds number. Perhaps most importantly, there would be no necessity to attempt modelling of ground interactions, or to question the representation of the physical validity of the experimental setup, as typically occurs in stationary-model configurations where rolling road and boundary layer suction techniques are required to ensure there is no gradient between fluid velocity and ground velocity.

Water tunnels have been used previously for low-speed experimental aerodynamics testing and flow visualisation, and this method is known to produce reliable results for fundamental research and early-stage conceptual design. Furthermore, water tunnels may even be regarded as the preferred option for flows of similar Reynolds numbers in model and full-size applications, and compare very favourably where the metric of return on effort (*viz.* value for money) is prioritised (Erm and Ol, 2012).

Research facilities such as water tunnels, channels and towing tanks have historically provided valuable information on the fundamental fluid dynamics of low-speed aerodynamic flows, especially in regions of unsteady vortical flows and ground proximity interactions (Erickson *et al.*, 1986).

Masuda and Suzuki (1991) numerically simulated the air-water interactions of a 2D WIG craft flying close to the free surface to assess the wavemaking effects and surface depression under the vehicle. They concluded that the effect on the surface is very small

due to the great difference in density between the fluids, and that the surface could be treated as a rigid wall.

Barber, Leonardi and Archer (1998b) also investigated the possibility of deformation of the non-rigid water surface beneath a flying WIG craft at various speeds. Using a fully viscous RANS solver with a moving grid that followed wave surface elevations, they determined that at very low speeds a small depression may be formed, although at typical operational speeds a local increase in surface elevation may occur. In all cases, the deformations were on the order of a few millimetres.

2.3.1 Fluid Similarity

Two different flows may be considered similar if the non-dimensionalised quantities, e.g. Froude number, Reynolds number, etc., are similar. For most practical cases regarding steady, external aerodynamic flows, only Reynolds and Mach numbers need to be matched. For low-speed applications, where $Ma < 0.3$, exact matching becomes less critical as an aerodynamic flow can be considered incompressible, regardless of the actual compressibility characteristics of the fluid (Katz and Plotkin, 2001).

In some specialised aerodynamic research water tunnels have been recognised as highly useful facilities for critical evaluation of complex flow fields, in particular those dominated by vortices and vortex interactions (Suarez, Kramer and Smith, 1994). Therefore, not only would water testing be suitable to replicate the aerodynamic flow characteristics in this low-speed regime but could be considered a superior method to provide a reliable indication of force and moment changes due to fluid interactions in ground surface proximity.

This technique would also be particularly useful for flow visualisation, due to the benefit of greater density and lower mass diffusivity of water compared to air. The Particle Image Velocimetry (PIV) method is widely used in towing tank environments and was planned to provide a 2D vector flow-field on the tank centreline, although this equipment was not available at the time of testing. Qualitative visualisation methods such as dye testing was deemed to be unsuitable due to necessitating filtering or draining and replacement of the tank contents after completion of testing.

2.3.2 Towing Rig & Wing Setup

A single profile was selected for testing, the DHMTU 10-40.2-10.2-60.21.5. This profile was developed specifically for GE use at some point after the bulk of the Russian experimental programme was completed. No existing published data was found for experimental results to be validated against, although this profile was one of the three included the CFD work package that provided numerical 2D aerodynamic coefficients over a range of heights and AoA.

Owing to the unconventional nature of this type of experiment, an off-the-shelf rig to mount on the towing carriage that would allow the wing to reach the bottom of the tank was not available. Therefore, a support structure that satisfied the constraints of orientating the wing in the correct attitude and height above the bottom was designed and fabricated. Aluminium was selected as the primary material due to handling and installation requirements and to minimise any unnecessary weight on the towing carriage. The construction drawing that was produced for fabrication at the on-site machine shop is shown in Figure 2-16.

Wing position had to be adjustable from the top of the tank to be able to complete a series of runs within a reasonable amount of time. Exact location and clearance to the tank bottom had to be measurable from above to avoid diving after every adjustment. Coarse positioning was carried out by releasing the end-caps and sliding the vertical arms to their approximate position before tightening slightly and completing fine positioning by way of vernier-type adjustment screws.

The cross section of the vertical mounting struts was as narrow as practicable to minimise parasitic drag or interference of the wing-generated pressure field. These were fabricated out of steel flat bar sections at the wing attachment points and as far up as possible, with chamfering on the forward and after ends to approximate a symmetrical airfoil shape, before transitioning to hollow round sections where the struts passed through the main transverse crossbeam. Calculation of the Strouhal number for the flow velocities indicated vortex shedding was not likely to occur. Satisfactory stiffness of the transverse crossbeam structure and mounting struts was critical to ensure reliable measurement of the forces and moments at the above-water carriage attachment points.

The pressure-transducer was a six degree-of-freedom ATI Omega 160 with IP68 enclosure. It was located above water, mounted on the upper surface of the main transverse beam. Ideally a multi-component strain gauge balance would have been incorporated into the model to more accurately measure the forces directly on the foil section, in a similar manner to pressure tapping, but this specialised miniature and waterproof equipment was not available. The rig-mounted transducer would be adequate to provide total lift force of the wing and rig system, loads which could only be generated by the wing itself.

The wing section was a hollow construction of a thin aluminium skin plated over five frames or formers to provide the correct shape. The span was as long as could be safely accommodated by the glass-sided tank, although it was recognised that a longer span extending to the tank sides would be more effective at replicating 2D flow over the foil. The chord length was determined to be as long as practicable whilst maintaining moderately high $AR > 4$ and Re around 1 000 000 at the highest towing carriage speeds.

The wing was sealed, although it was not necessary for it to remain watertight, as there were no electronics or other measuring equipment located inside. Pressure taps were intended to be included inside the wing for direct measurement of the flow-field but it was not possible to acquire the equipment.

Mounting points were located either side at the quarter-chord position at the forward end and a single centrally located strut at the trailing edge fixed the angle of incidence for each configuration.

A turbulence-inducing strip was located at $0.1c$ from the leading edge, using sand-type particles added to the surface finish. It is common practice to encourage turbulent but attached flow over hydrodynamic models at this scale, as this would be representative of the full-size flow conditions.

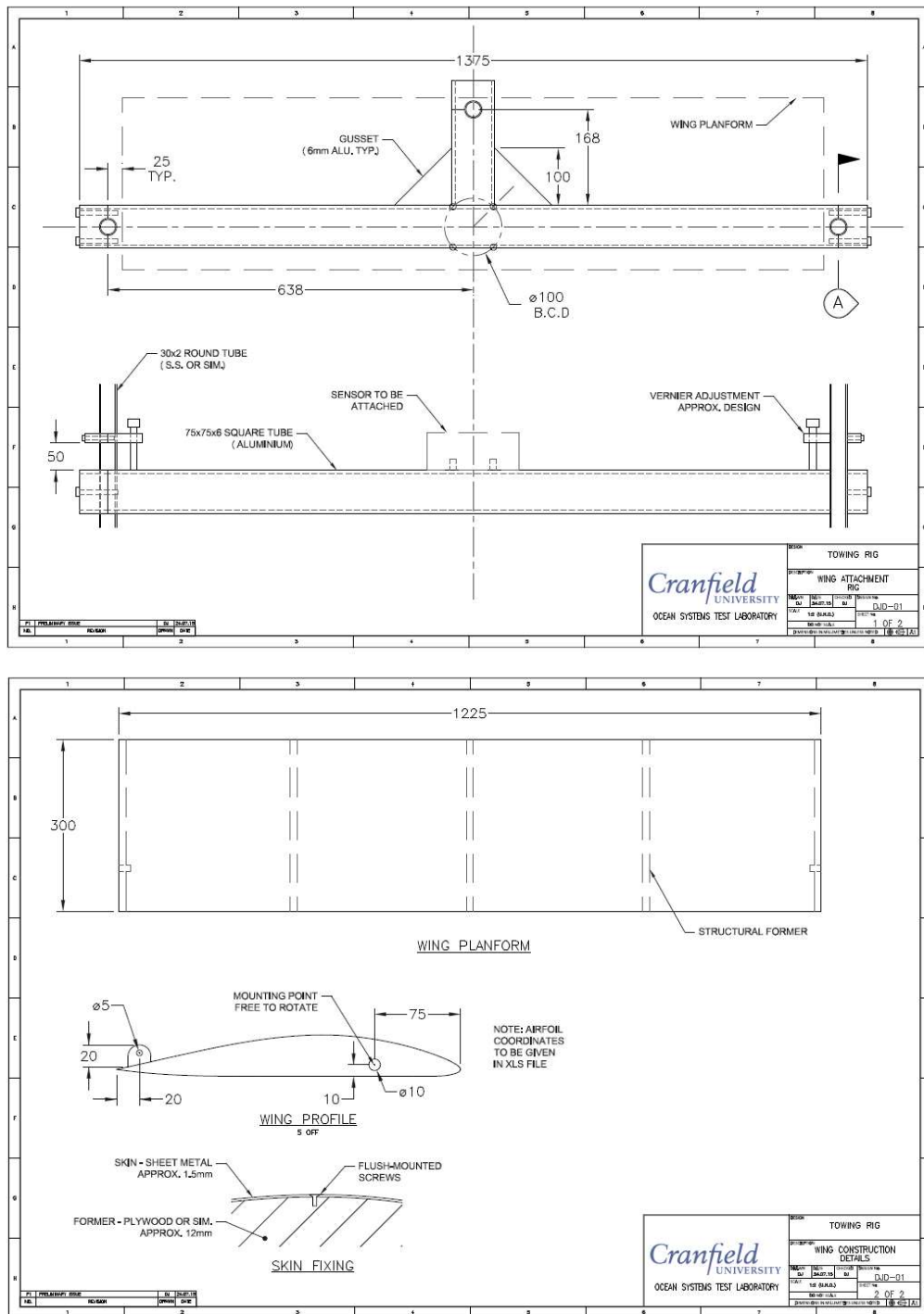


Figure 2-16 Construction drawings for the towing rig and carriage interface (upper) and the wing structure and mounting details (lower)

2.3.3 Calibration and Sampling Frequency

The data acquisition system needed to be set up with suitable sampling parameters for the test programme. The sampling parameters to be selected were frequency, i.e. the number of raw data points collected over a given time period, and smoothing or averaging, i.e. how many samples were averaged either side of a given raw data point. The raw sampling frequency dividing by the smoothing value results in the effective sampling rate.

The wing was set up in the tank and initial runs were carried out to ensure the coordinate system of the transducer was orientated correctly and measuring reasonable values. The sampling parameters were then varied over several runs and the force outputs were measured and averaged to arrive at a single value for a given configuration.

Figure 2-17 below shows three variations that were used to assess the sensitivity of the effective sampling frequency on the output values and measured standard deviations. The three rates were:

- i. 100 Hz (raw) @ 10 smoothing = 10 Hz (eff.)
- ii. 300 Hz (raw) @ 6 smoothing = 50 Hz (eff.)
- iii. 1000 Hz (raw) @ 10 smoothing = 100 Hz (eff.)

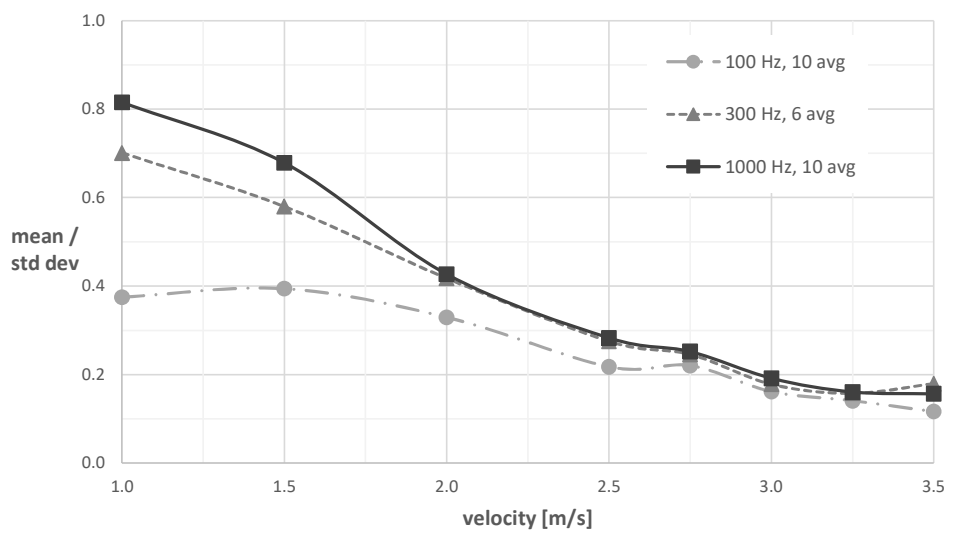


Figure 2-17 Ratio of mean force to standard deviation for three sampling combinations

As the plot shows the ratio of mean measured output to standard deviation for each velocity, the lower ordinate values correspond to a more tightly grouped data set. The lowest velocities show the greatest scatter, although at 1 m/s this ratio for 10 Hz is approximately half that of the 50 Hz and 100 Hz combinations. Across all sampling frequencies, the ratios converge to similar levels as velocity increases, effectively rendering the higher velocity runs more accurate or reliable with less scatter.

2.3.4 Test Matrix

The highest Reynolds number that could be tested in this particular tank was on the order of 1 000 000, due to limitations on maximum carriage speed, carriage towing force available and the size of model that would fit.

Before determining how many speeds would be run for each configuration of angle and height, the sensitivity analysis was carried out to determine how the output forces were influenced by the sampling rate and smoothing. Once this was done a matrix of angles, heights and towing velocities to be tested was developed. The combinations are summarised in Table 2-5 for a total of 90 runs

The CFD analysis included TE heights at $h/c = 0.05$, as this could be achieved with sufficient precision in the meshing and domain blocking. For the experimental programme, this lowest height was not included as the flatness of the bottom of the tank was measured and found to have elevation differences up to 6 mm. This was not a constant offset that could be accounted for through adjustment of the model but a random variance in longitudinal and transverse flatness. Therefore, required precision could not be reliably achieved when attempting to position the wing 15 mm from the tank bottom.

Table 2-5 Test matrix of experimental runs completed

<i>Reynolds Numbers</i>	<i>Angles</i>	<i>Heights</i>	
$\times 10^6$	deg	h/c	
0.45	-4	0.1	
0.75	0	0.2	
1.05	4	0.3	
	8	0.5	
	12	0.75	TOTAL
		1.0	RUNS
3	5	6	90

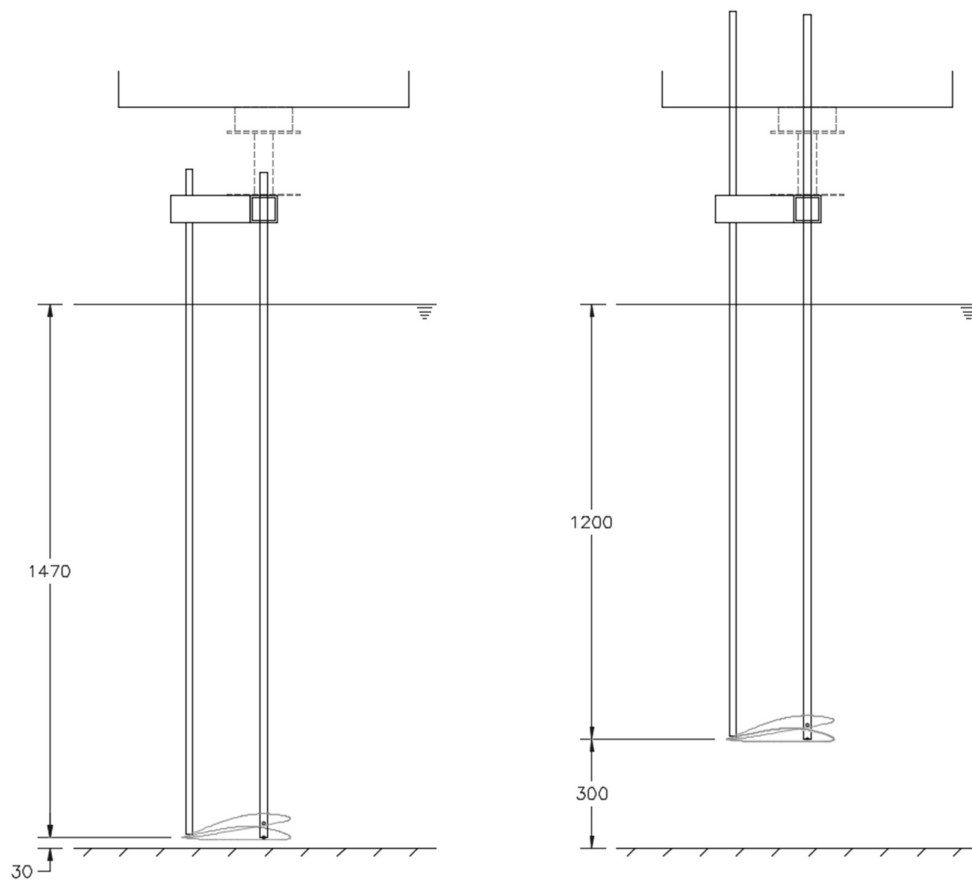


Figure 2-18 Diagram of wing heights in tank at lowest (left) and highest (right) positions

3 Results

Following on from the format of the previous section, the results of the experimental and computational work will be divided into their respective categories. The data in this section is arranged as follows:

- (a) Experimental hydrodynamic testing of the hull model in the high-speed towing tank (Section 3.1);
- (b) Computational results of the 2D CFD programme to determine aerodynamic coefficients for three profiles and their suitability for use IGE (Section 3.2);
- (c) Experimental testing of an aerodynamic wing profile IGE using a novel towing tank technique (Section 3.3).

Further investigation and analysis into the results presented in this section can be found in the Discussion, Section 4.

3.1 Experimental Hydrodynamics

Four displacements were tested across the speed range in the zero-trim condition. As the displacements decreased, i.e. the vessel effectively becoming lighter due to an external upwards force, lower speed runs were omitted. This was done as the lifting surfaces that would provide this external force would not be effective at those speeds.

Three further displacements were tested with a fixed stern-down trim of 3° to represent a small rotation angle that could be beneficial during the take-off phase. It is common practice in GA procedures to rotate the craft once an appropriate take-off speed has been reached which results in increased lift to unstick from the surface. During seaplane take-off, this rotation angle is greatly reduced compared to that for a solid runway as the craft cannot rotate about the main landing gear but instead is constrained by the water pressure along the length of the floats. Planing surfaces are generally quite sensitive to running trim angles and a sudden rotation could result in a large increase in drag that either slows down the vehicle or requires much greater power input to maintain take-off speed.

The main characteristics of interest for this novel hullform were:

- i. Overall hull resistance and its variation with height.
- ii. Hull suction (negative lift) and its variation with height.
- iii. Total pitching moment acting on the hull in various configurations.

3.1.1 Data Processing

After the initial set-up tasks of sensor calibration and determination of sampling frequency were completed, the model testing programme began with raw data being collected for each of the test run configurations. As the points of interest were the forces and moments for each discrete velocity, the acceleration and deceleration regions at the beginning and end of the runs were truncated to isolate the recorded values at the specified steady-state velocity.

For runs under 5 m/s, the data acquisition was stopped after 30 seconds in order to save the time taken in continuing the run and then to reset the carriage at beginning of the tank. After this elapsed time, 3000 samples had been collected for these runs and any data acquisition impact on accuracy of results was deemed negligible. Figure 3-1 shows the relationship between carriage speed across the tested range and the elapsed time of data collection. As the sampling frequency remained constant at 100 Hz, the number of samples is directly proportional to elapsed time.

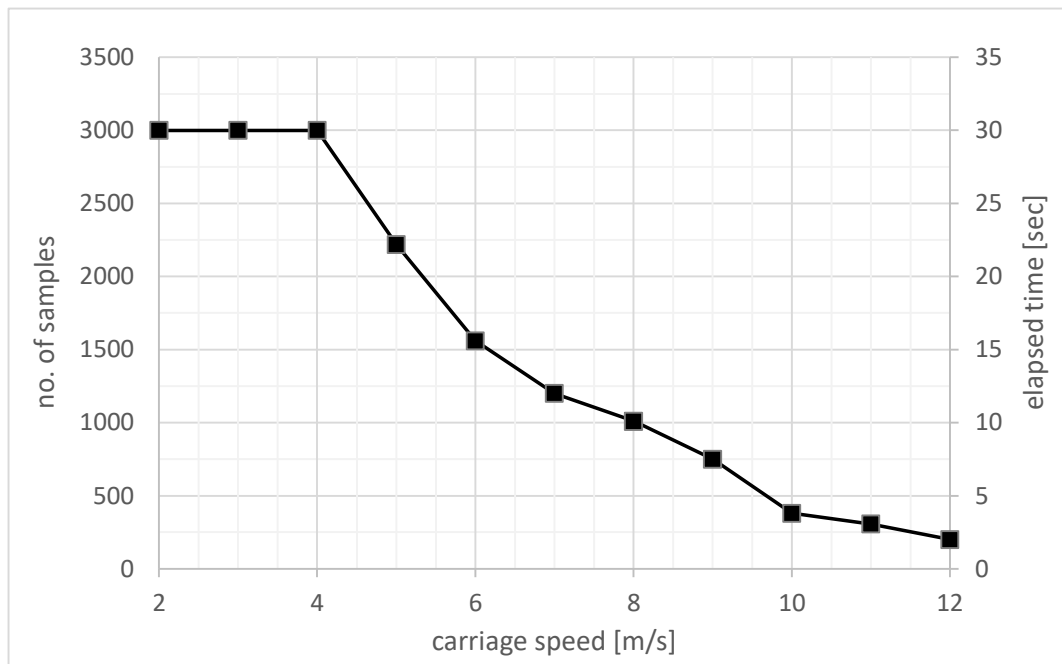


Figure 3-1 Number of samples & elapsed time of data collective at varying carriage speeds

Each configuration to be tested was run down the tank a single time, unless an obvious procedural error had occurred, *viz.* not waiting long enough for the surface to settle, carriage speed slightly too high or low, problem with data acquisition, etc. As many of the runs benefitted from long collection times, repetition of runs was decided to be unnecessary. However, the data collection windows for the higher speeds were obviously shorter, with runs at 10 m/s and above under 5 seconds.

The full tank length was utilised for these runs, which understandably caused the greatest amount of wavemaking due to the high speeds, so the required time in between subsequent runs, in order to allow reflected waves to attenuate and water surface to settle, was necessarily the longest. As time at the facility was extremely limited and several model configuration changes were still scheduled, repeat runs could not be carried out at that stage. Ideally, each of the runs would have a similar dataset in terms of number of samples collected, thereby similar collection times at each specified velocity, resulting in 6-12 runs for each of the three highest speeds.

Arguably, the highest speed runs could use even longer time at steady-state than the lower speed runs, as there is more carriage vibration, wave fluctuation and general background noise to be filtered from the signal. Fortunately, in this particular application, the results from the highest speeds in the full displacement condition are also some of the least important. This is due to the WIG operational profile, as by this time in a take-off run aerodynamic alleviation effects would result in the hull functioning as a much lighter craft, whereby one of the reduced-displacement resistance lines would be more appropriate.

In typical naval architectural model-testing practice, total resistance of the bare model is the primary metric, as measured by resistance to forward motion (global coordinate x-direction). Frictional resistance can be calculated as a function of wetted surface area and a frictional resistance coefficient derived from one of a number of possible sources. An estimate of viscous resistance, essentially a form factor based on similar vessel types, can then be made.

The largest component of the remaining force is generally referred to as wavemaking resistance, which dominates at higher speeds for many vessel types. For dynamically supported craft, spray generation and topside wetting may be significant and their generation also absorbs non-negligible energy.

In this case the individual resistance components were not estimated, as optimising for the lower speed range was not a primary objective. The limiting resistance would be expected at the higher end and would predominantly come from the dynamic interaction of a practically flat bottom skimming along the water surface.

In order to assess reliability of the measured data, the standard deviation of each data set was calculated and expressed as a percentage of the mean value. As expected, the slower runs had larger standard deviations as the signal-to-noise ratio is typically higher for when the signal is smaller or weaker. One standard deviation ranged from 7% of the mean value at 12 m/s/ to just over 17% of the mean value for the 6 m/s runs. Typically, the percentage of the mean represented by one standard deviation could be broadly considered to be 12-15% across the range.

3.1.2 Test Results

Figure 3-2 shows total resistance for the model in the 0° trim condition. The 100% displacement case refers to the full immersed volume the hull is designed to displace hydrostatically. The 80% case is expected to be representative of the same vessel under the influence of an external lifting force equivalent to 20% of the vessel weight. As this is intended to be provided by the aerodynamic surfaces, this force can be considered ‘aerodynamic alleviation’.

As this alleviation increases as forward speed increases, the hullform was further tested in the 50% and 25% displacement cases, representing 50% and 75% aerodynamic alleviation respectively.

In the 100% displacement condition at 10 m/s, the recorded drag appears lower than the trend indicates. Test procedures were not altered for this run, nor was any model adjustment or alignment required. Data acquisition and analysis methods were also the same. It is not clear why this point is lower than expected, although spray generation may be at least a partial cause, the effects of which are discussed in Section 4.1.

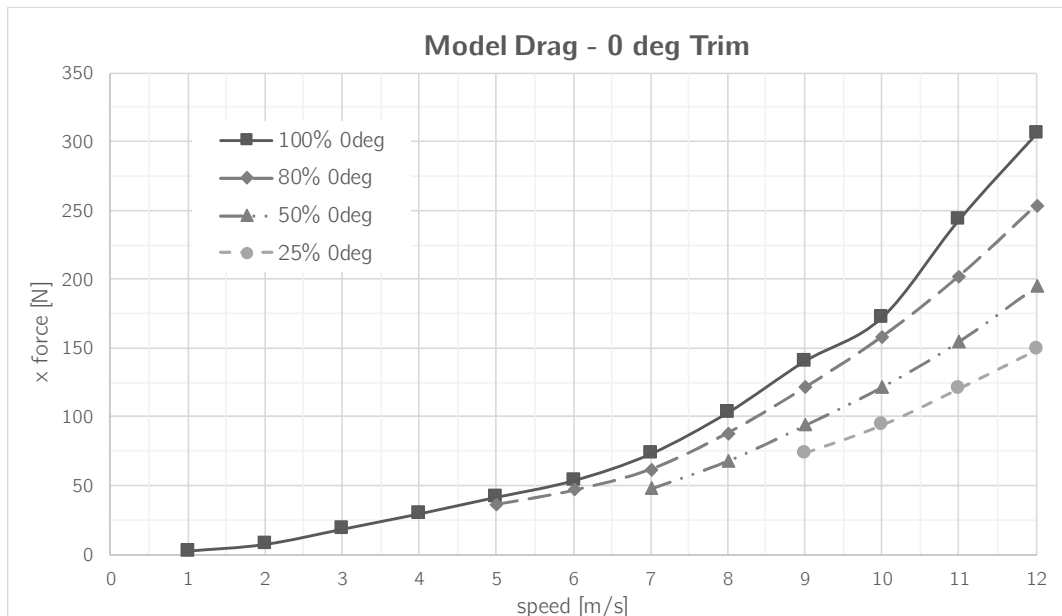


Figure 3-2 Model drag for varying displacements at 0° trim

High speed marine craft often have flat buttock lines, viz. longitudinal sections parallel to the centreplane of the vessel. The rationale is to keep the water flow as horizontal as possible, as a vertical component to the wake or spray induces a vertically downwards reaction upon the after part of the vessel. This downwards force typically causes the stern to squat and will require an increase in the magnitude of the upwards force to compensate. As this is a force opposing positive upwards force, or lift, it is termed suction.

The model hullform was designed with an excessive amount of rocker by conventional standards. Rocker is defined as the amount of curvature in the longitudinal section, i.e. as seen in a profile view. For comparison, planing craft are based on prismatic forms; by definition a prismatic hull would have zero rocker. Therefore, this amount of rocker was expected to generate some amount of suction but the magnitude was unknown prior to testing.

The suction force would act in opposition to the lifting force provided by the aerodynamic surfaces. Some amount of suction would be acceptable, especially in the lower speed range, as sufficient power would typically be available to continue vessel acceleration. The highest values in Figure 3-3, produced by the 100% displacement case at the greatest speeds, are expected in the test results but would never be seen in actual operation. If the hull were not getting sufficient lifting force to move across the resistance curves at this point of the take-off phase, the vehicle would not be able to lift clear of the surface.

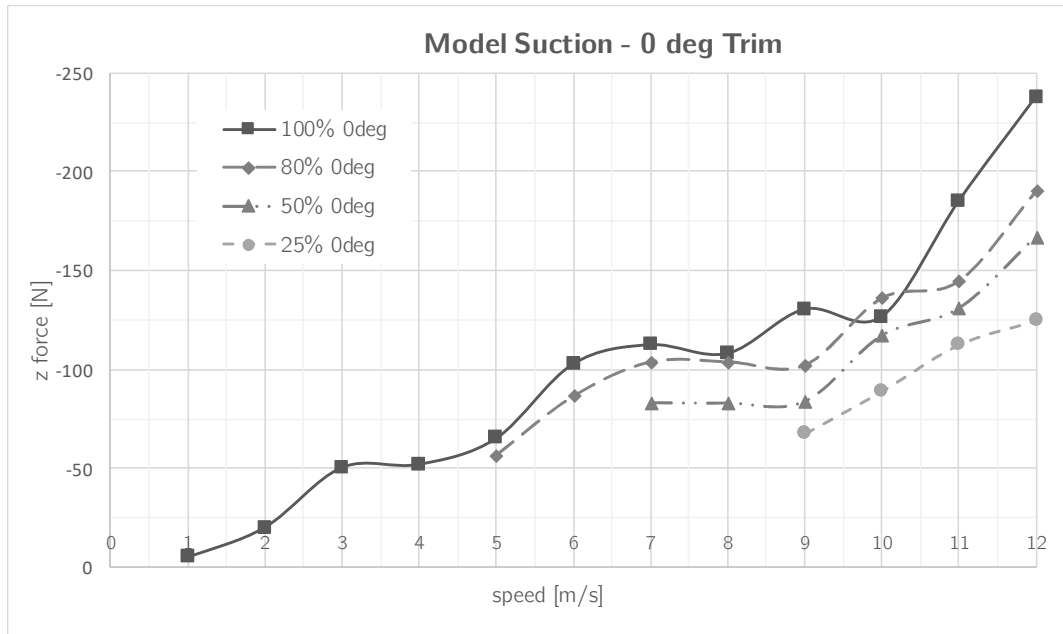


Figure 3-3 Model suction for varying displacements at 0° trim

As the model was not free to trim, a longitudinal moment was measured in addition to the orthogonal lift and drag forces. The majority of the measured moment consisted of the drag force acting on the hull bottom, caused by the distance from the measurement transducer, resulting in a nose-down moment. This spurious moment was calculated by estimating the vertical location of the drag force centre of effort and determining the lever arm for a given height and attitude from the CAD model. This moment was then subtracted from the measurements of each configuration to determine the physical pitching moment.

As shown in Figure 3-4, the hull initially creates a bow-down moment in the lower part of the speed range across all displacements. However, by the time 8 m/s is reached the moment has become bow-up. This effect should aid the vessel in creating lift by increasing angle of attack of the aerodynamic lifting surfaces, allowing it to unstick from the water surface.

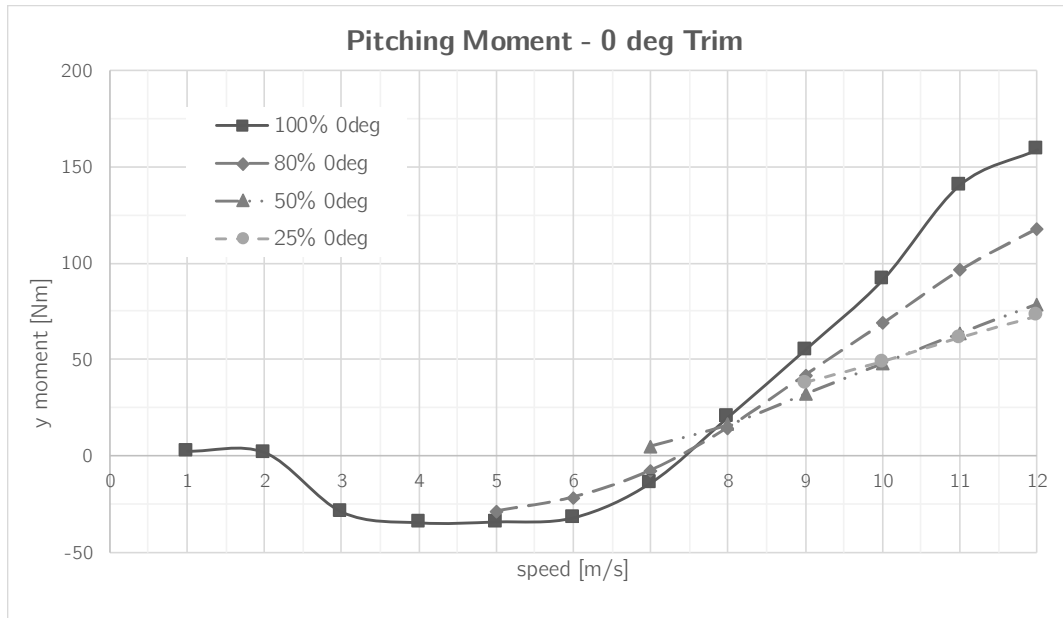


Figure 3-4 Model pitching moments for varying displacements at 0° trim (positive = bow up)

In addition to the even keel, or 0° trim cases, a limited number of runs were carried out with 3° of bow-up trim. The resistance was expected to be approximately similar to 0° trim or potentially higher, as the waterlines would become bluff-bowed at this attitude. The aft buttock lines were intended to become flatter with respect to the water surface and possibly begin to produce a net positive upwards force.

Figure 3-5 and Figure 3-6 show the drag and suction forces for the three displacement cases tested in this trim condition.

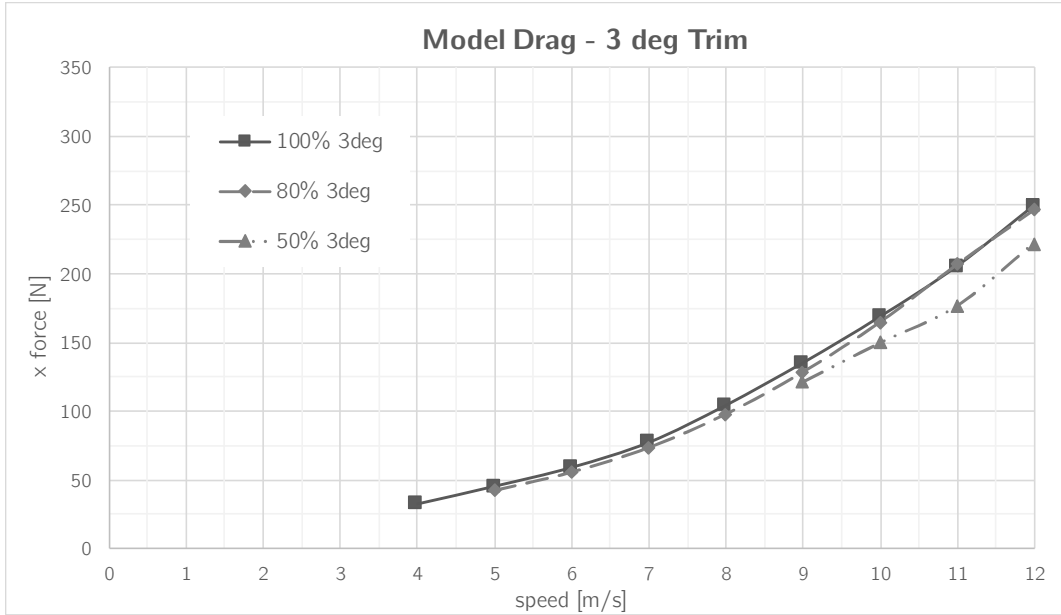


Figure 3-5 Model drag for varying displacements at 3° trim

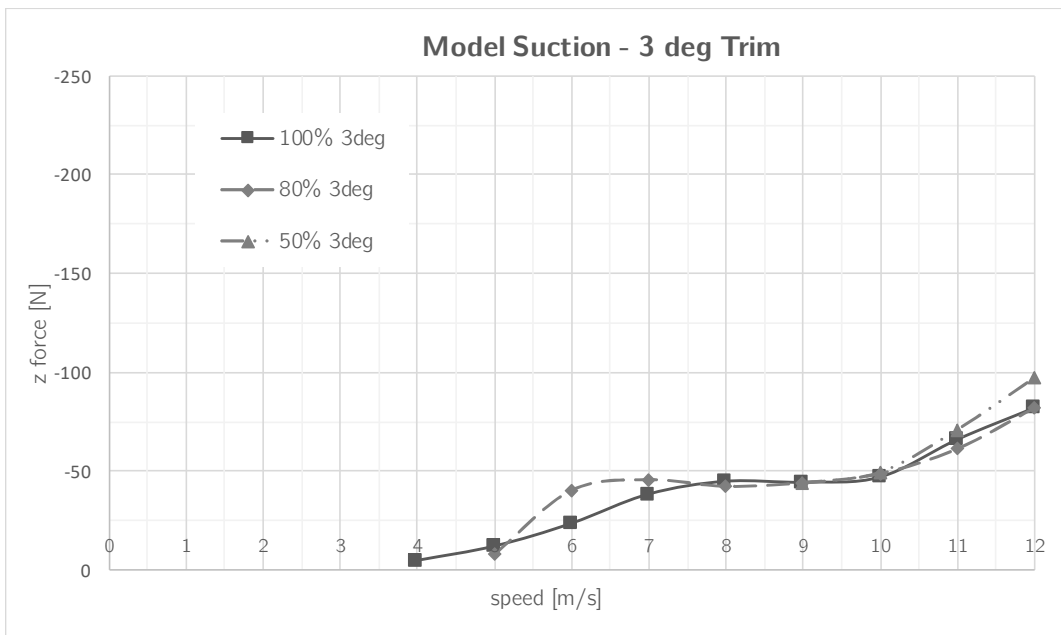


Figure 3-6 Model suction for varying displacements at 3° trim

The pitching moment was corrected in the same manner as described previously and is shown in Figure 3-7. As the moments are all negative, the effect on the model was nose-down, increasingly so at the highest speeds.

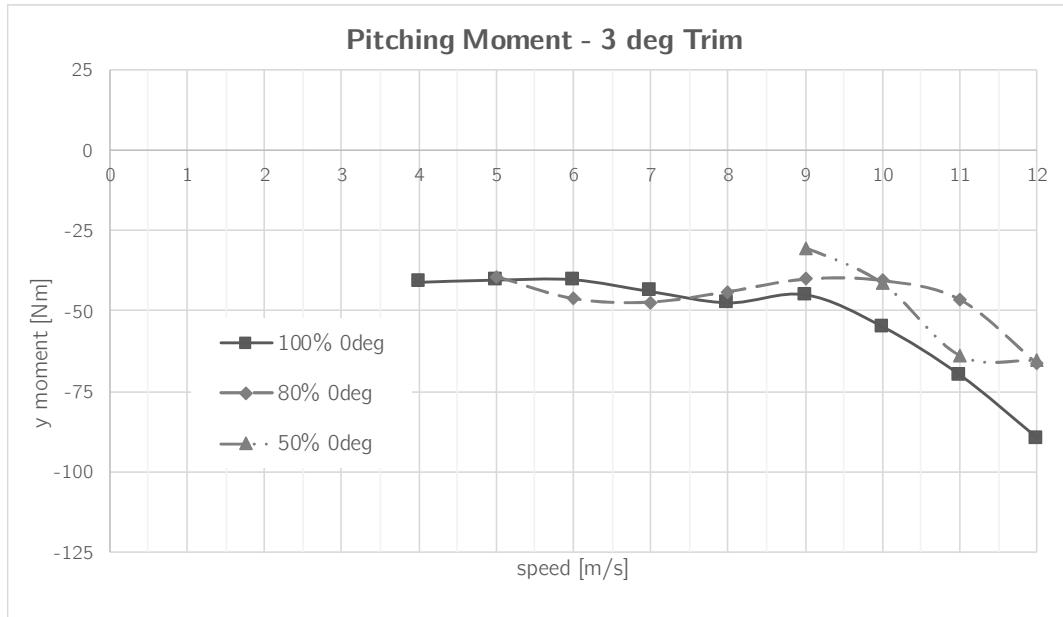


Figure 3-7 Model pitching moments for varying displacements at 3° trim (positive = bow up)

3.1.3 Repeat Test Runs

As described in Section 3.1.1, repeat test runs were generally not able to be carried out unless an obvious error was discovered during the real-time data analysis or a procedural error occurred. However, upon subsequent analysis and graphical display of the data, it appears that certain results could benefit from repeated runs.

As mentioned in the previous section, several data points for the 10 m/s 100% displacement run appear anomalous. Firstly, Figure 3-1 indicates a somewhat reduced number of samples compared to the surrounding runs. If all test procedures were carried out consistently, approximately 20% more sampling points could be expected.

This anomaly is found in the main resistance plot in Figure 3-2 where the measured drag is slightly lower than might be expected from the surrounding data. The plot of negative-lift suction in Figure 3-3 also shows an unexpected dip for this run. Although all of the displacements demonstrate an undulating response, it appears that the suction force should be considerably greater, around 40% or near -175 N, to be consistent with the behaviour of each of the other reduced-displacement conditions. The pitching moment plot appears inconclusive.

Taken together, this data is indicative of an experimental error, unlikely to be due solely to a reduced number of samples acquired, but by any account very difficult to pinpoint after the fact.

Also as touched upon in Section 3.1.1, it may appear that all of the higher speed runs could benefit from additional runs to bring their time of data acquisition more closely to that of the lower speeds. As described previously, this is not necessarily the case due to the unique nature of WIG operation. Indeed, these highest speeds may prove the least useful data points as they should never be experienced in practice.

Certainly, once a model design has been refined and is ready for a more mature performance assessment, accurate measurement of the forces and moments in the transitional regime would be of the utmost importance. Numerous test runs should be undertaken to ensure accuracy of experimental data in this region.

Reduction of suction and drag forces should lead directly to lower take-off speeds and potentially powering requirements, respectively, whilst hydrodynamic pitching moment couples directly with the wing-generated moment to determine the overall running trim and aerodynamic angle of attack of the wing surfaces.

3.1.4 Uncertainty Assessment

Due to the nature of these early-stage feasibility experiments intended to identify general trends, a formal method of uncertainty analysis, e.g. as set out in the ITTC guidelines for uncertainty analysis in towing tank tests (ITTC, 2008a), was not rigorously followed. The ITTC states that the purpose of their document is to assess uncertainties in data collection and analysis stemming from the ITTC resistance test procedures.

As these procedures are intended for conventional vessels travelling at typical marine speeds, where often a high degree of precision is required for contractual reasons or otherwise, this level of resolution was determined to be unachievable and unnecessary.

Nevertheless, a qualitative assessment to identify limitations in the collection of the data is useful to characterise the overall impact of sources of uncertainty on the measured data and subsequent conclusions drawn. Three main sources have been identified, with a brief explanation of each.

Measurement sensor calibration or positioning. The transducer that was used had been employed in many other tank testing programmes and after initial calibration was unlikely to be the direct source of significant error. However, the positioning of the sensor on a short stalk above the model, attached to the underside of the towing rig (see Figure 2-6) was perhaps less than ideal. Axial forces, i.e. global x,y,z coordinates, should have been measured accurately but the pitching moment values needed to be transposed from the sensor location to the waterplane. In addition, the moment contribution of the drag force lever arm to the sensor height needed to be deducted from the raw measurement to calculate inherent pitching moment. An improved technique for moment capture would be highly recommended.

Side wetting and magnitude of spray formation. The bare model had no features to reduce or eliminate side wetting or spray generation. Coupled with a radiused bilge, keel rocker and high topsides, side wetting and spray was significant. The stochastic nature of this phenomena indicates that the measured forces due to their influence may not necessarily be the same for multiple runs of the same configuration. This is covered in more detail in Section 4.1.

Measurement and analysis errors. In theory, these should amount to near zero. In practice, they never are as errors creep in due to the nature of physical model testing and processing of raw experimental data. Rigorous procedures and measuring techniques are specified to mitigate these effects but it is not possible to take a measurement without a margin of error. Multiple measurements, in this case test runs, are helpful to reduce these types of errors. Anomalous results have been discussed in the previous sections.

With these factors in mind, qualitative assessment of overall uncertainty can be estimated. As context is essential, this experimental programme was designed with top-level foundational research in mind. As such, the data appears satisfactory to show proof of concept. There are numerous issues that could be improved upon for future work, many have been highlighted, although the exact nature of which would depend on the scope of the future project.

As some rudimentary statistical analysis was carried out during the data analysis stage, an approximate quantitative assessment can also be attempted. By assigning nominal values to the factors listed in this section, a rough estimate of the overall combined errors can be made. Anomalous results previously described notwithstanding, the expected margin of error for any given data point should be within +/- 20%, an acceptable level of accuracy for this initial stage of testing.

3.2 Computational Aerodynamics

The primary purpose of the CFD programme was to determine an accurate database of aerodynamic coefficients for three representative profiles of distinct family types: conventional GA, reflexed, and GE specific. Reliable values of lift, drag and moment, and recognising inherent behaviours of the family types IGE, provide a solid foundation for future WIG design. Lift and moment are the most relevant parameters in this analysis, as drag is highly dependent on turbulence modelling in RANS solutions and highly influenced by geometric configurations in full-size vehicles.

The NACA 4412 is characteristic of conventional cambered profiles for GA usage. Maximum camber is 4% of the chord, which occurs at 40% of the chord length from the leading edge. Maximum thickness $t/c = 0.12$. Data is available for OGE conditions and fortunately this is also one of the most widely tested profiles IGE. This profile was used during the validation of the CFD setup and results.

The NACA 25112 is typical of tailless or flying-wing profiles. Thickness of this profile is also 12% but the main difference to the 4412 is the reflexed, or S-shaped, camber line. This profile also has a lower surface with more constant offset from the chord line, resulting in a flatter bottom without the droop similar to the 4412 at the forward end. Advantages of using this type of section include utilising smaller empennage control surfaces or possibly eliminating them altogether. However, no GE test data was found for this profile.

A family of airfoils designed specifically for WIG use was developed by the Department of Hydromechanics at the Marine Technical University, St. Petersburg (DHMTU) for the next-generation Ekranoplan program. These profiles are characterised by a reflexed camber line and straight lower surface which may be orientated completely flat (horizontal or parallel to chord) or at a small angle. The DHMTU 10-40.2-10.2-60.21.5 was developed specifically for GE usage but public data of its performance is not available. The selection of this profile was based upon the 12% thickness and long flat section along the bottom.

A straighter lower surface was expected to perform better at very low angles of attack, without causing downward suction due to a convergent-divergent flow restriction that generally occurs when conventional profiles are placed close to a solid boundary. This appears to be due to high fluid velocities between the nose radius and the point of maximum section thickness, which result in negative pressures with respect to the freestream velocity, on what should be the pressure face. Minimum pressure is reached at maximum thickness before a pressure recovery phase begins with lower fluid velocities, although pressures remain negative until the trailing edge is reached (Ahmed and Sharma, 2005).

The intended effect of a reflexed camber line is to reduce nose-down pitching moment, although at the cost of reduced lift. WIG craft can compensate for this reduced lift by either increasing the size of the main wing surface or by operating with an increased AoA. There are drag implications for both of these options but the advantage is keeping the main lifting surface inside the GE zone and reducing tail control surfaces.

The following subsections will break down the results in terms of lift, moment and drag in an attempt to organise this data in sensible manner. Although the primary intent of this work package was to reliably predict values for lift and moment, drag results have also been computed and made available.

For every configuration of angle and height, detailed results and plots are presented in Appendix 8.7, 8.8 and 8.9 for the NACA 4412, NACA 25112 and DHMTU 10-40.2-10.2-60.21.5 profiles, respectively.

3.2.1 Aerodynamic Coefficients - Lift

The reaction forces and moments the airfoils experienced in the flow conditions were normalised against the profile chord length to produce aerodynamic coefficients. By assessing these reactions in coefficient form, the test data can be applied across a wider range of applications and performance can be compared to other profiles in different test conditions.

Typically lift, drag and moment reactions are plotted against AoA. Thin airfoil theory states that lift is proportional to AoA and the lift-curve slope is linear across most of the operational range of the profile. At the upper limit, lift generally breaks down with the onset of stall, i.e. flow along the upper surface no longer stays attached and breaks off causing large downstream vortices. Drag increases significantly while lift decreases.

As WIG craft tend to operate at much lower AoA, a narrower range was analysed, from -2° to 10° (the NACA profiles were run up to 9°). The lift coefficients generated by these three profiles are shown in Figure 3-8 through Figure 3-10 as a function of AoA.

Furthermore, as GE lift is also highly dependent on height above ground, the lift coefficients can be represented as a function of height, as shown in Figure 3-11 through Figure 3-13.

The plots indicate that the NACA 4412 generally produced the greatest lift at a given AoA although the performance of the DHMTU profile is not far behind. The NACA 25112 c_l is lowest for any given AoA.

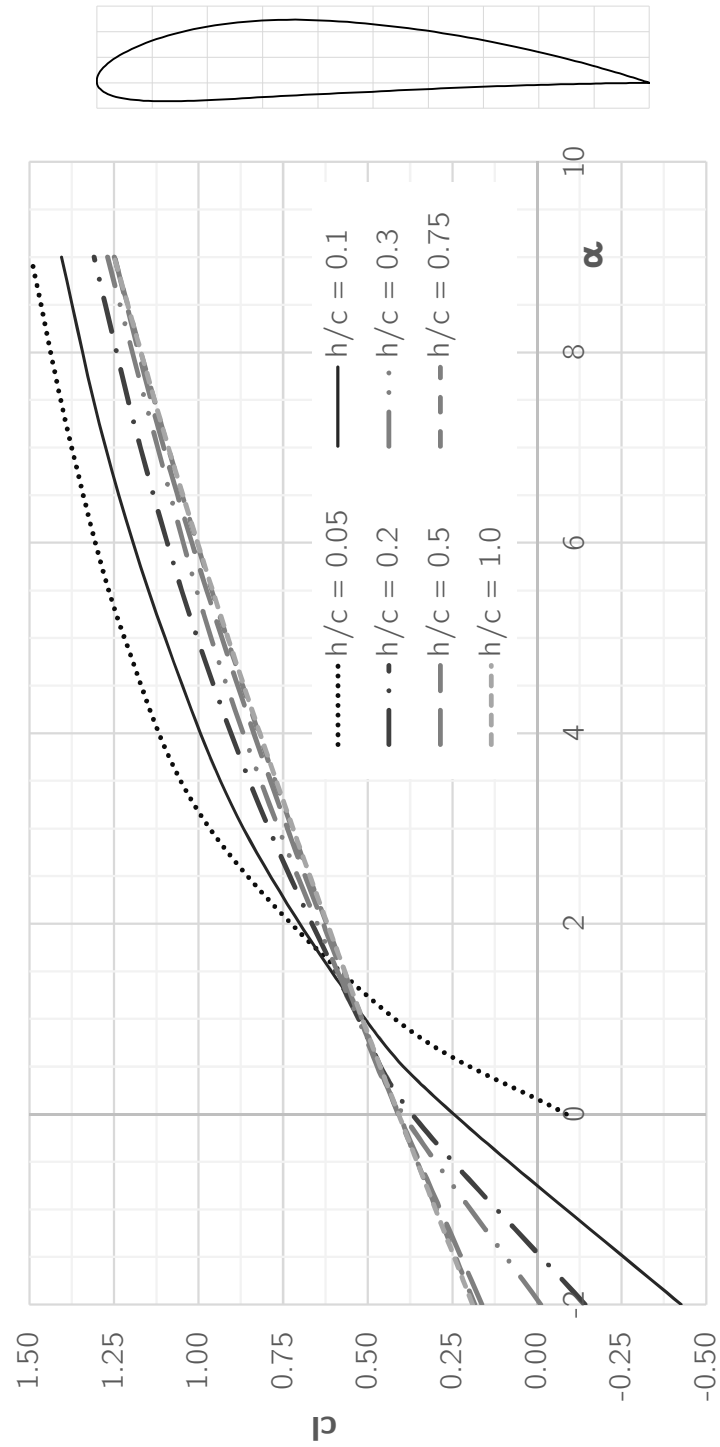


Figure 3-8 Lift coefficients at varying angles of attack for NACA 4412

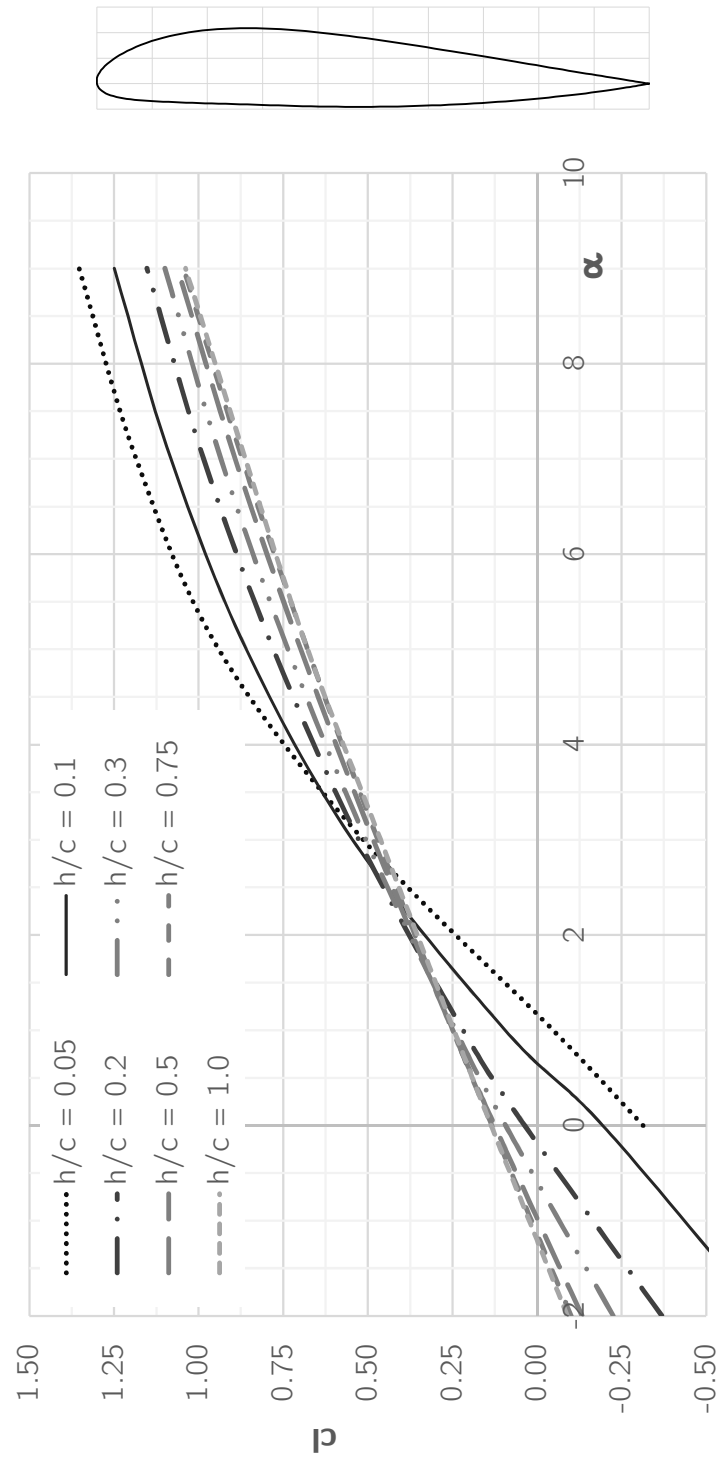


Figure 3-9 Lift coefficients at varying angles of attack for NACA 25112

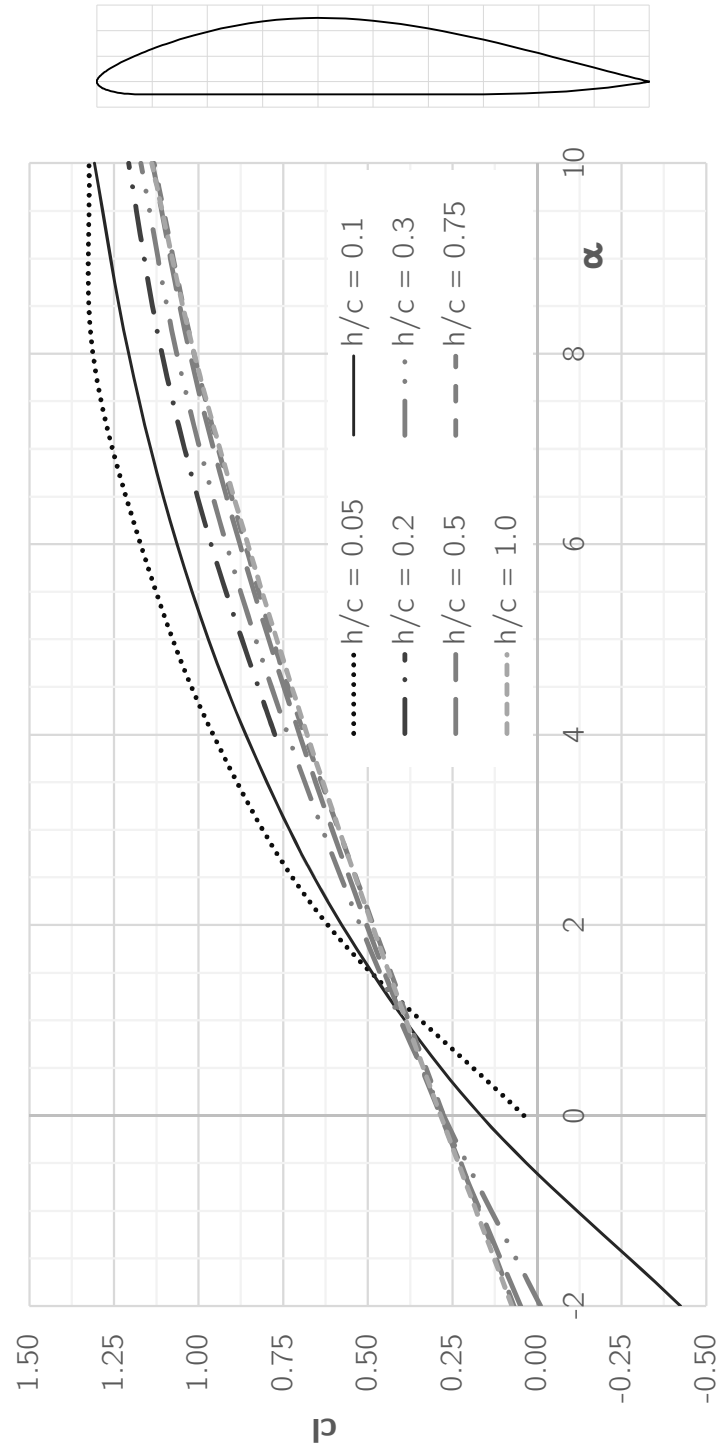


Figure 3-10 Lift coefficients at varying angles of attack for DHMTU 10-40.2-10.2-60.21.5

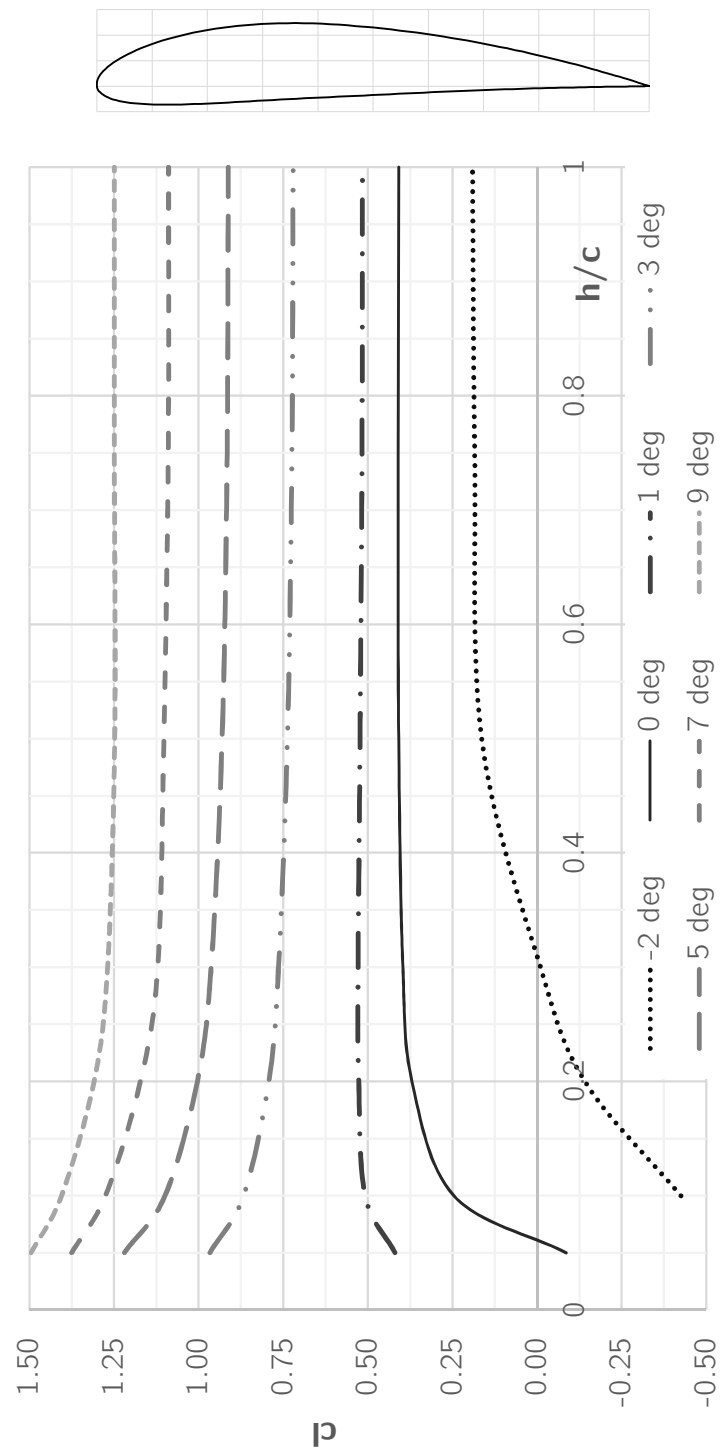


Figure 3-11 Lift coefficients at varying heights above ground for NACA 4412

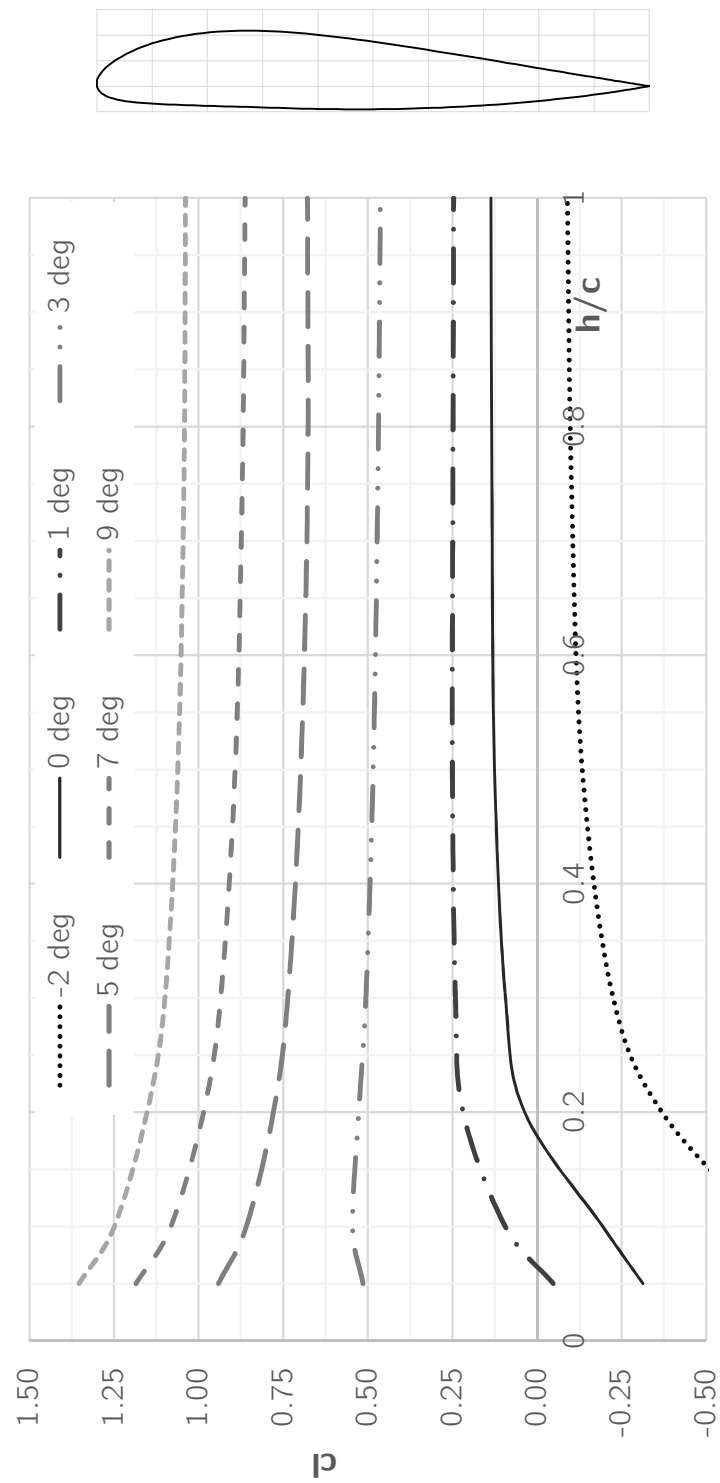


Figure 3-12 Lift coefficients at varying heights above ground for NACA 25112

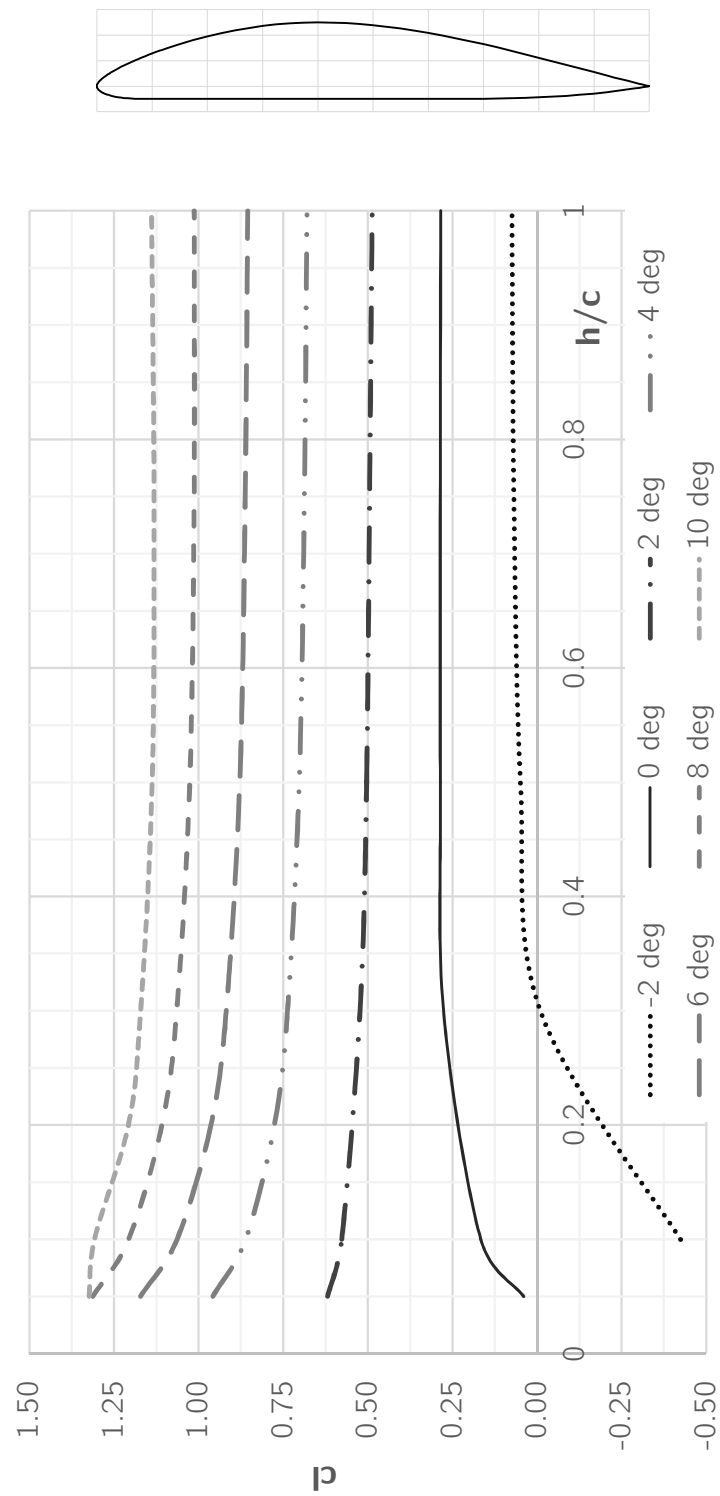


Figure 3-13 Lift coefficients at varying heights above ground for DHMTU 10-40.2-10.2-60.21.5

3.2.2 Aerodynamic Coefficients - Moment

In a similar manner as done for the lift coefficients, the variations of moment coefficients can be represented with respect to AoA and height above ground, shown in Figure 3-14 through Figure 3-16 and Figure 3-17 through Figure 3-19, respectively.

The moments here are taken about the trailing edge, as this provided an easily definable point that could be referenced on all of the profiles. This aided computational setup and was the datum for positioning the profiles using the scripted approach as previously described. This way, the fundamental moment characteristics of the different profiles can be compared qualitatively, noting the changes in magnitude and positive or negative direction across the AoA or height ranges.

Generally in typical aerodynamic literature, moment coefficients are stated with respect to the Aerodynamic Centre (AC) of a given profile. This is not as straightforward in GE applications, as determining the location of the AC can be problematic. However, these moments were transformed from TE to AC as shown and discussed in Section 4.2.3.

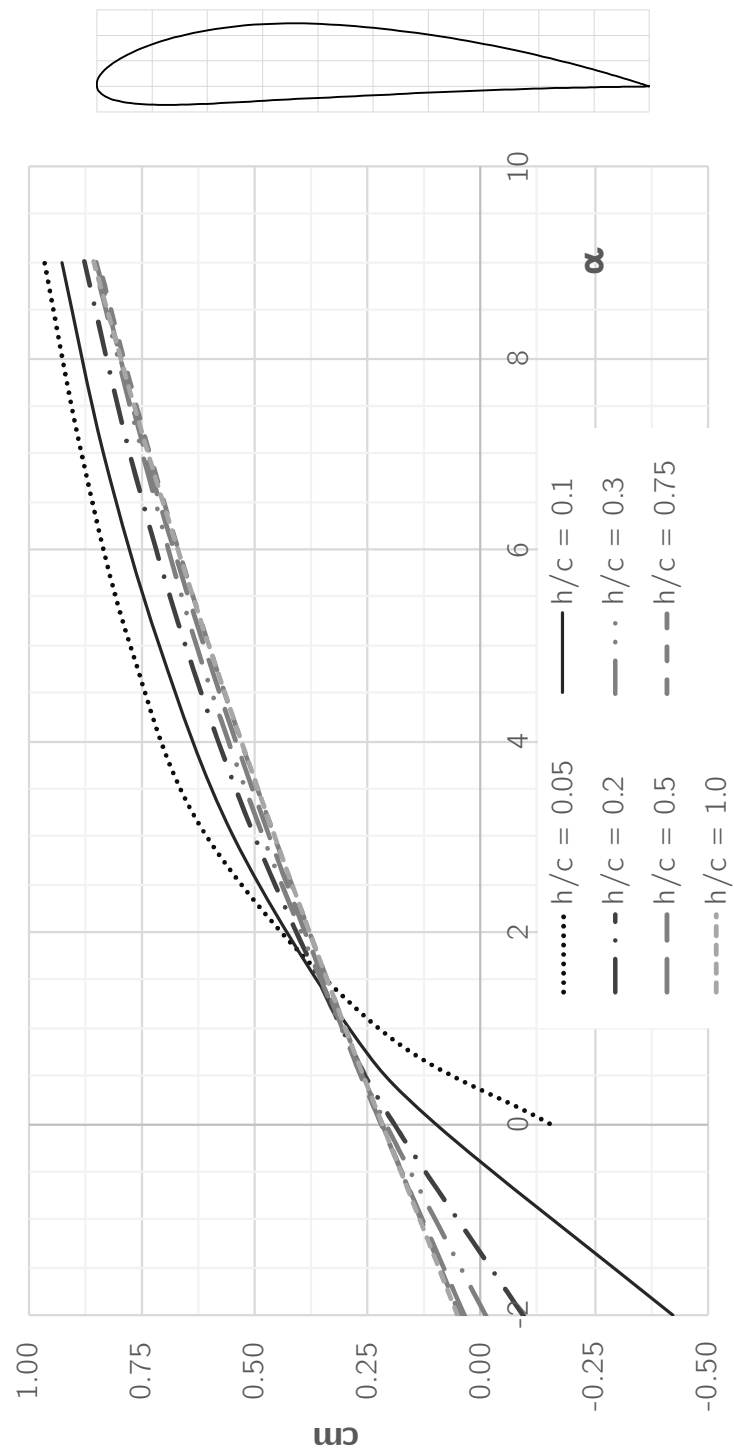


Figure 3-14 Moment coefficients at varying angles of attack for NACA 4412 (from TE)

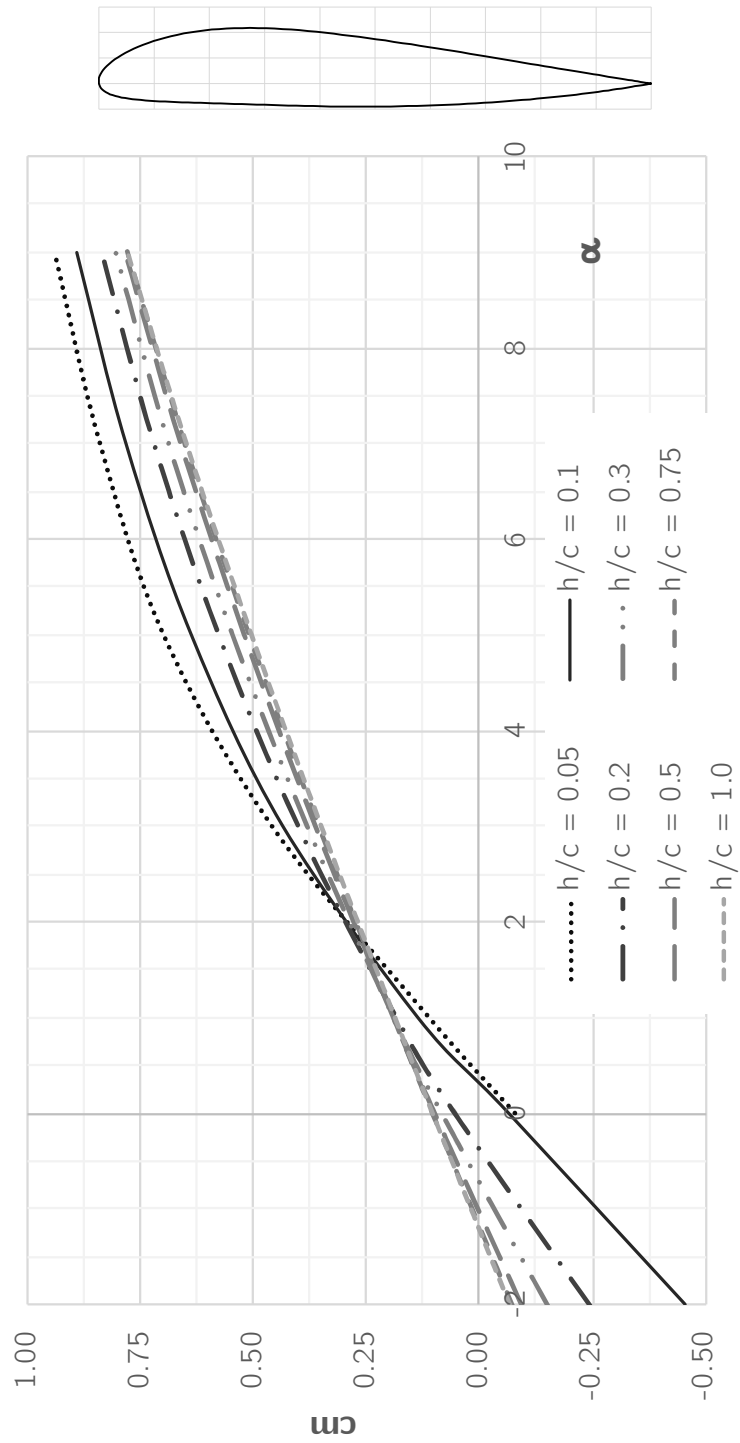


Figure 3-15 Moment coefficients at varying angles of attack for NACA 25112 (from TE)

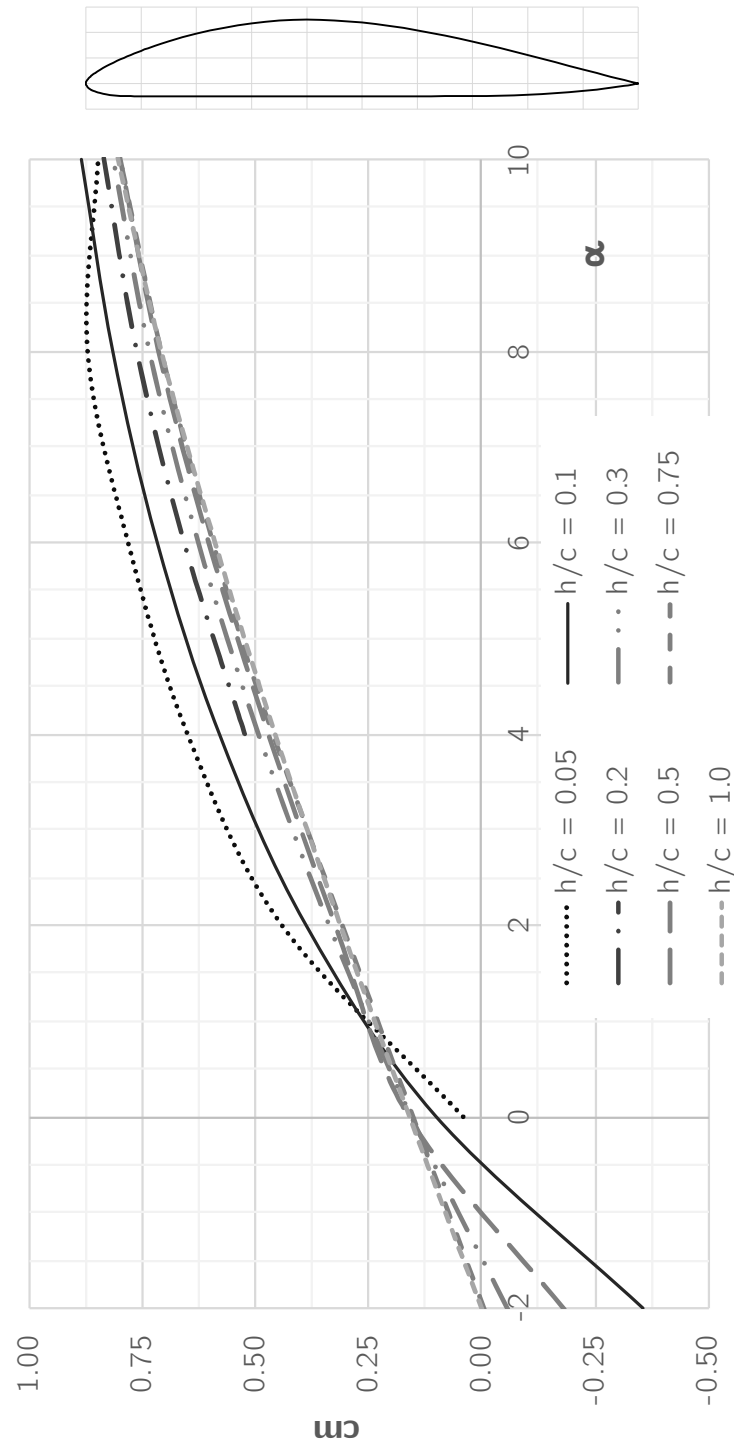


Figure 3-16 Moment coefficients at varying angles of attack for DHMTU 10-40.2-10.2-60.21.5 (from TE)

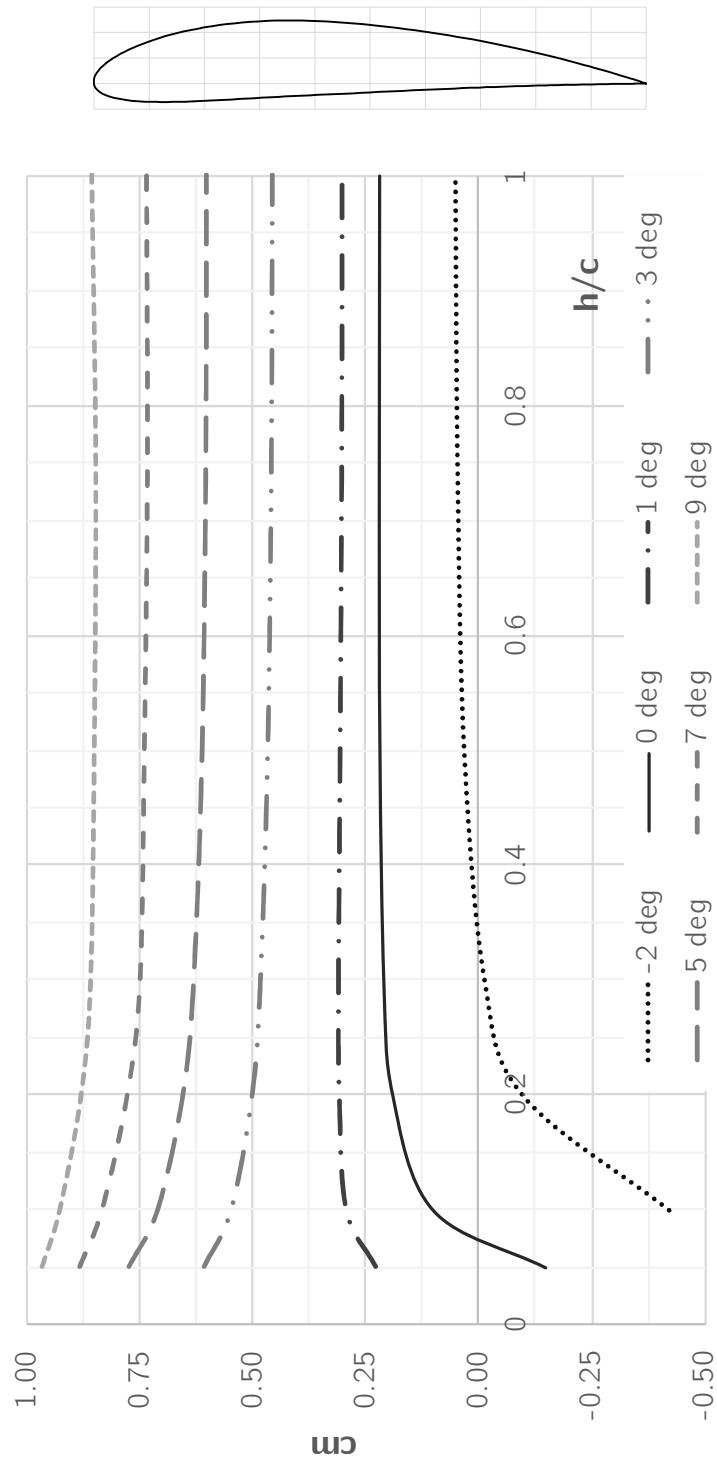


Figure 3-17 Moment coefficients at varying heights above ground for NACA 4412 (from TE)

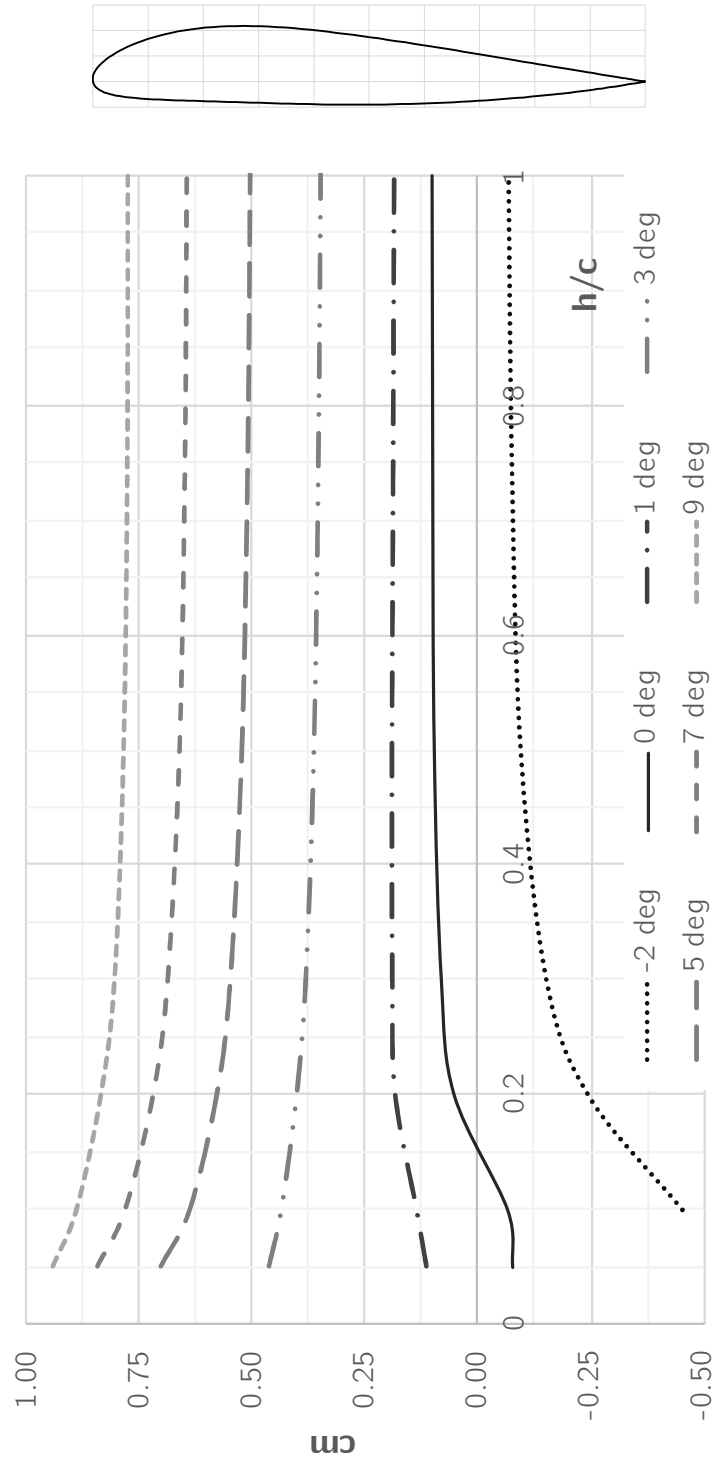


Figure 3-18 Moment coefficients at varying heights above ground for NACA 25112 (from TE)

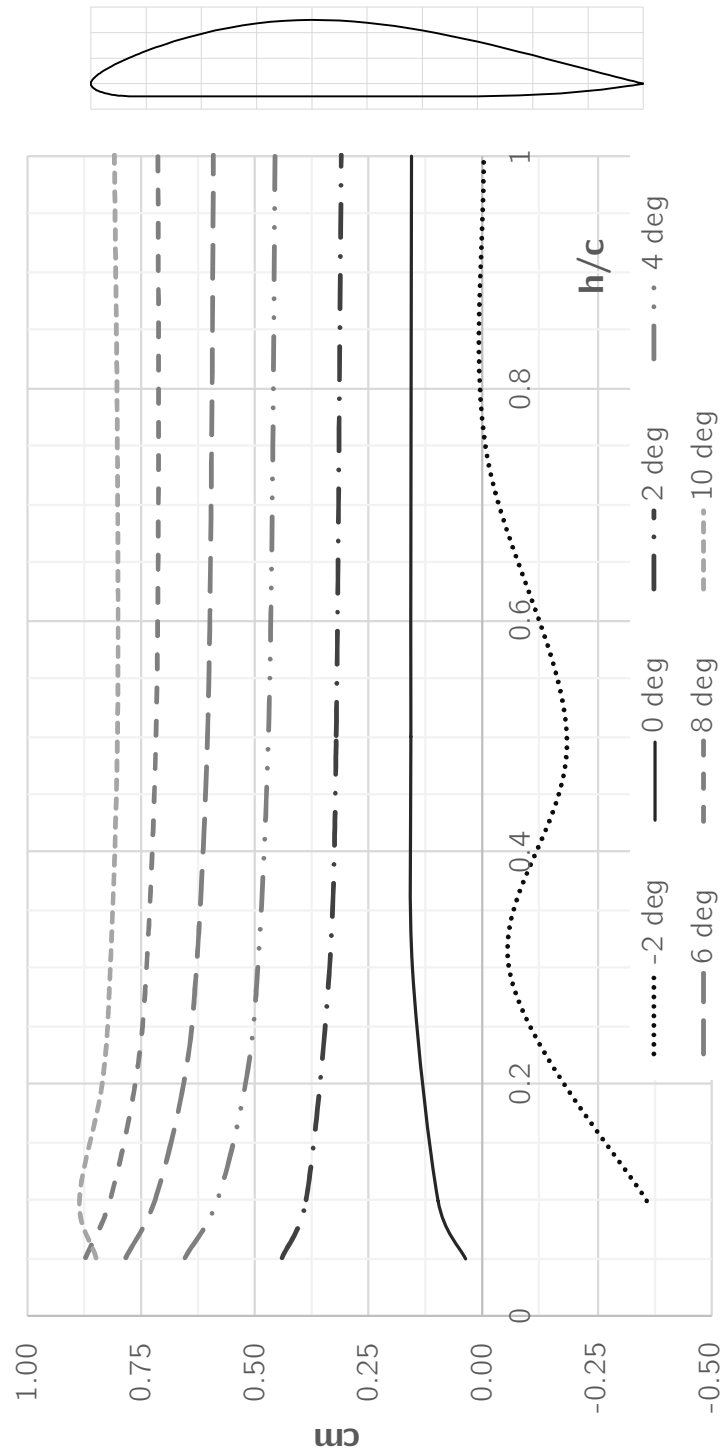


Figure 3-19 Moment coefficients at varying heights above ground for DHMTU 10-40.2-10.2-60.21.5 (from TE)

3.2.3 Aerodynamic Coefficients - Drag

Although drag performance was not a primary objective of this analysis, careful selection of an appropriate turbulence model (see Section 2.2.1.2) and ensuring suitable mesh resolution in the inflation layer to capture boundary layer effects (see Section 2.2.1.3) resulted in well-ordered drag estimates. As these are RANS solutions the drag forces are highly dependent on wall functions and capturing the correct laminar to turbulent transition points.

As presented for the lift and moment coefficients, the variations of drag coefficients can be represented with respect to AoA for different values of h/c or with respect to height above ground for different values of AoA, as shown in Figure 3-20 through Figure 3-22 and Figure 3-23 through Figure 3-25, respectively.

All three profiles demonstrate an identifiable drag bucket with respect to AoA, for the lowest heights, $\bar{h} \leq 0.1$. The increase in drag at shallow angles occurs first and most evidently in the 25112 profile, where drag at $\bar{h} = 0.05$ increases significantly for $\alpha < 4^\circ$. This increase occurs more gradually for $\bar{h} = 0.1$ until $\alpha \approx 0^\circ$ where there is a sharp increase. For $\bar{h} \geq 0.2$, all heights show this drag increase at the shallower angles.

The 4412 profile shows a similar tendency of increased drag at $\bar{h} \leq 0.1$ for $\alpha < 2^\circ$, although the effect is less pronounced. For the remaining heights, drag for $\alpha \geq 0^\circ$ increased with AoA as expected. Interestingly, the lowest heights produced greatest c_d as AoA increased, indicating a blockage effect at the TE.

The DHMTU profile produced the flattest c_d curves of the three. The trend of increased drag for $\alpha < 2^\circ$ at the lowest heights was still present, although much reduced compared to the NACA profiles. However, for $\bar{h} \geq 0.2$ this increase is not seen and the c_d across all heights remained moderate until the largest AoA was reached.

This indicates the DHMTU may be expected to be an efficient airfoil for GE operation, for moderate AoA and heights, as lift increases in this region without much drag increase. This effect is discussed in Section 4.2.2.

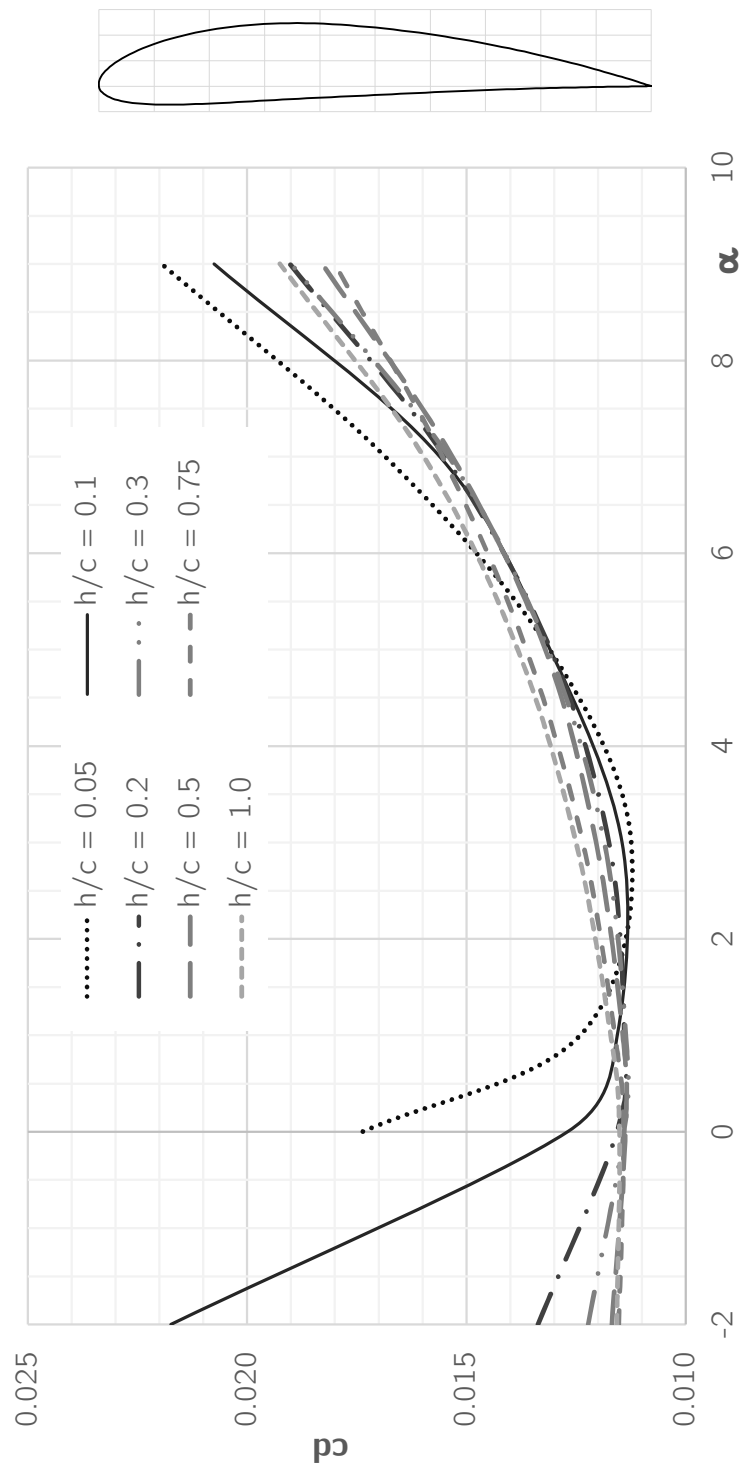


Figure 3-20 Drag coefficients at varying angles of attack for NACA 4412

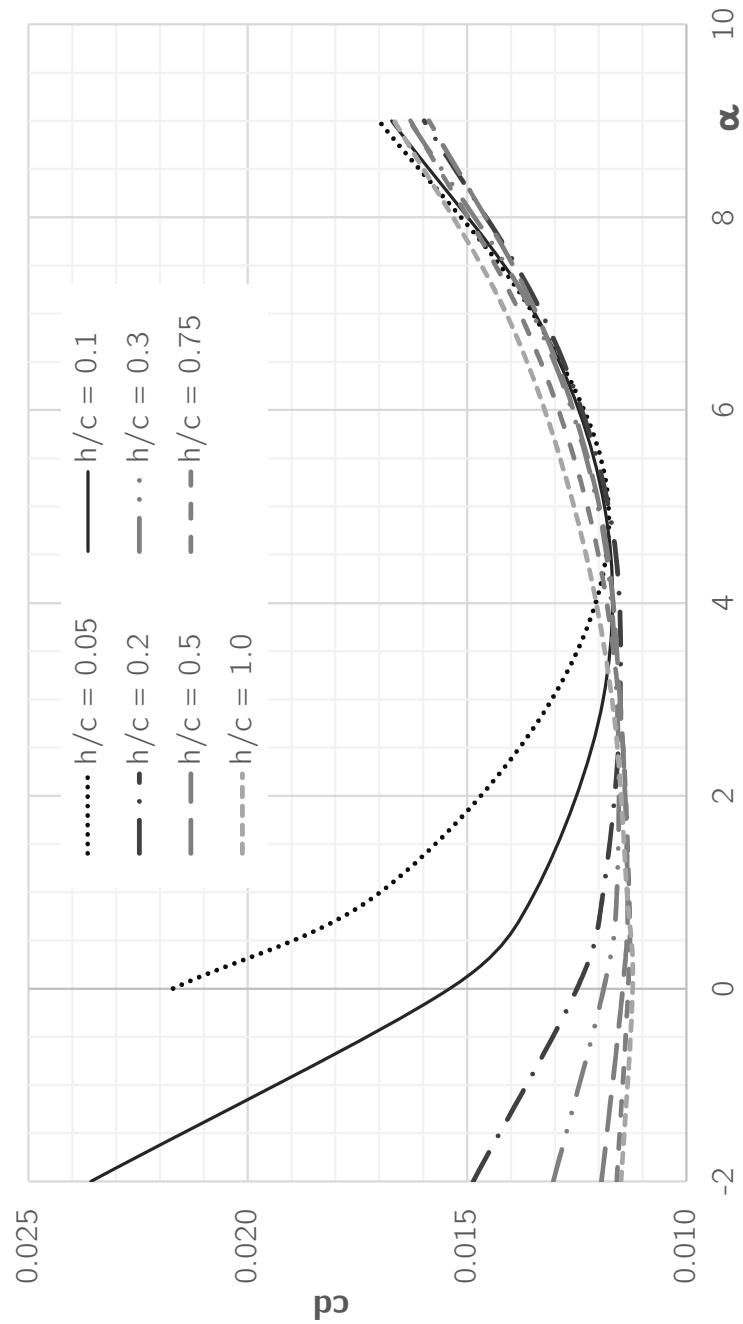


Figure 3-21 Drag coefficients at varying angles of attack for NACA 25112

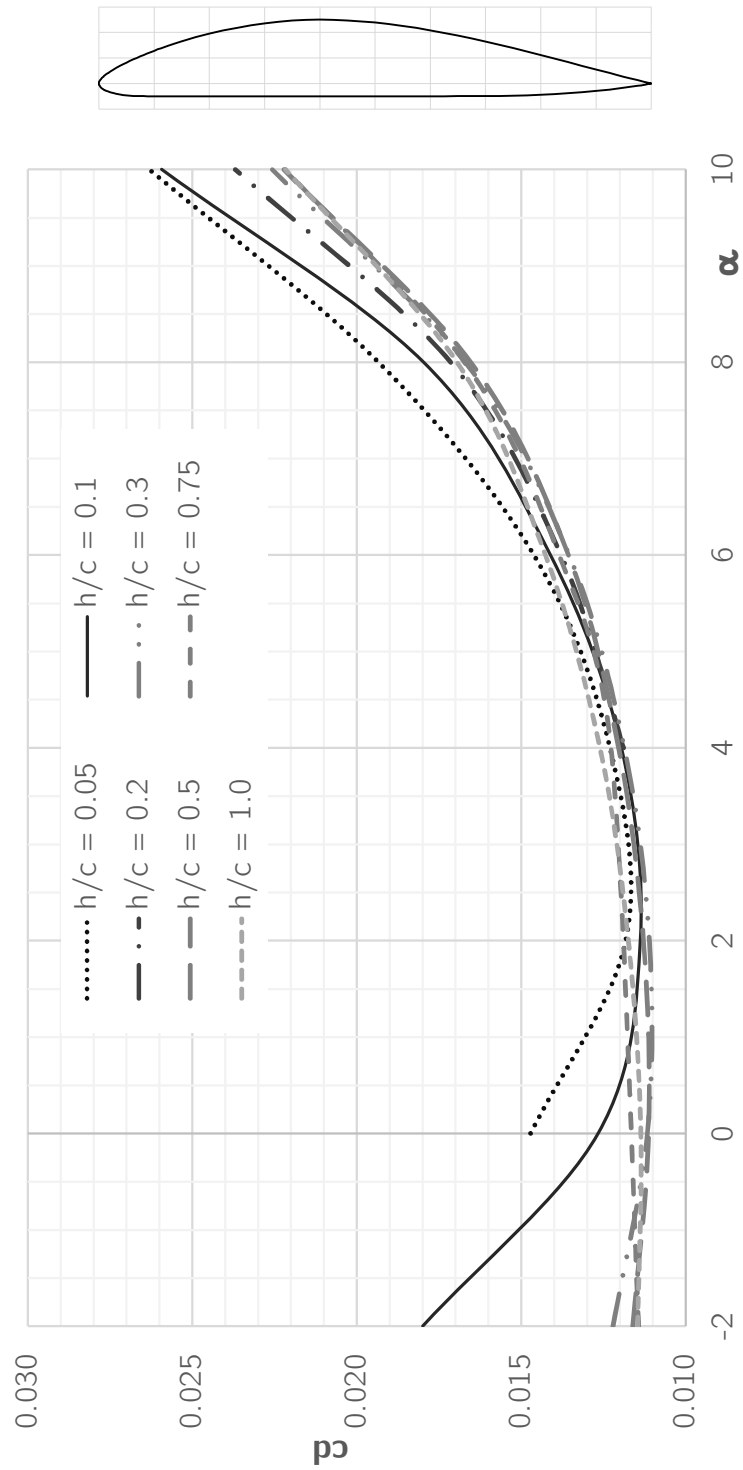


Figure 3-22 Drag coefficients at varying angles of attack for DHMTU 10-40.2-10.2-60.21.5

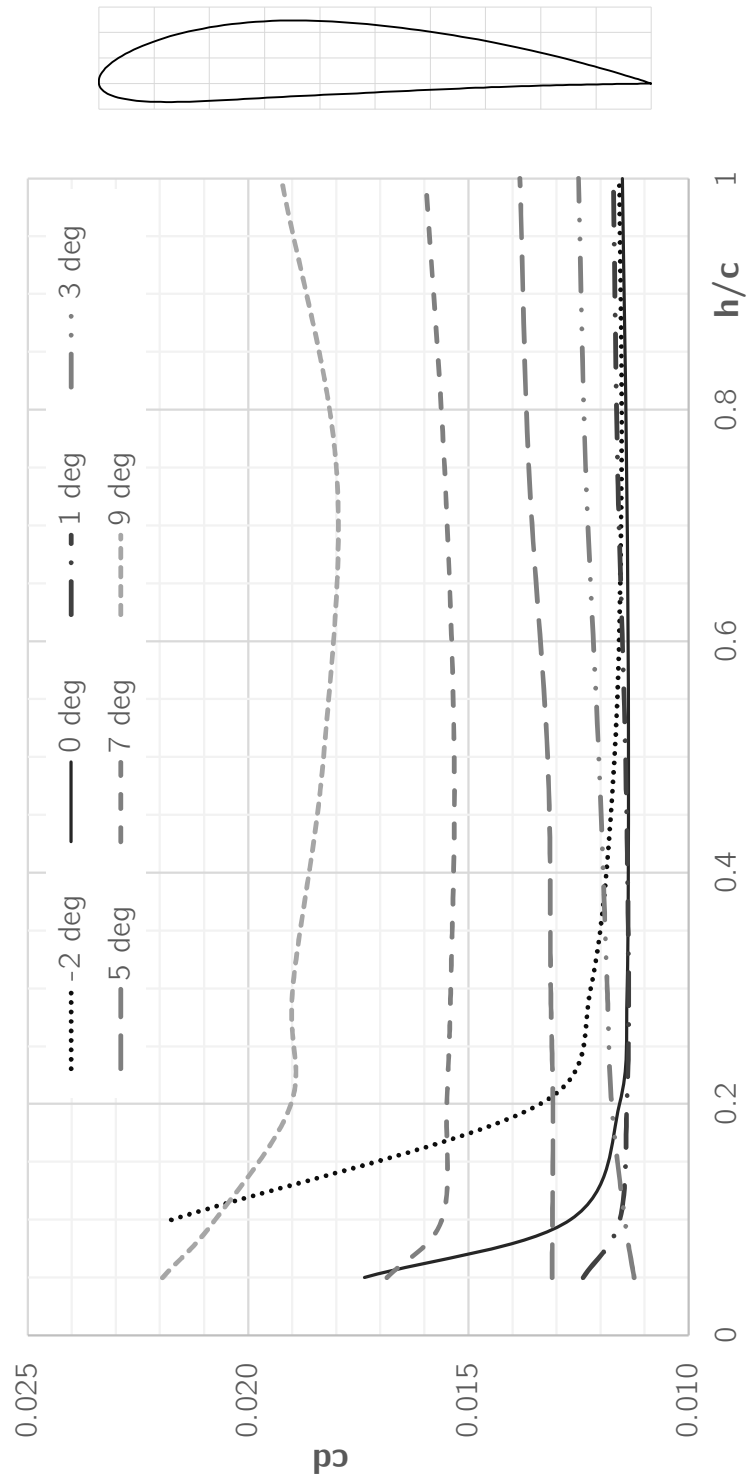


Figure 3-23 Drag coefficients at varying heights above ground for NACA 4412

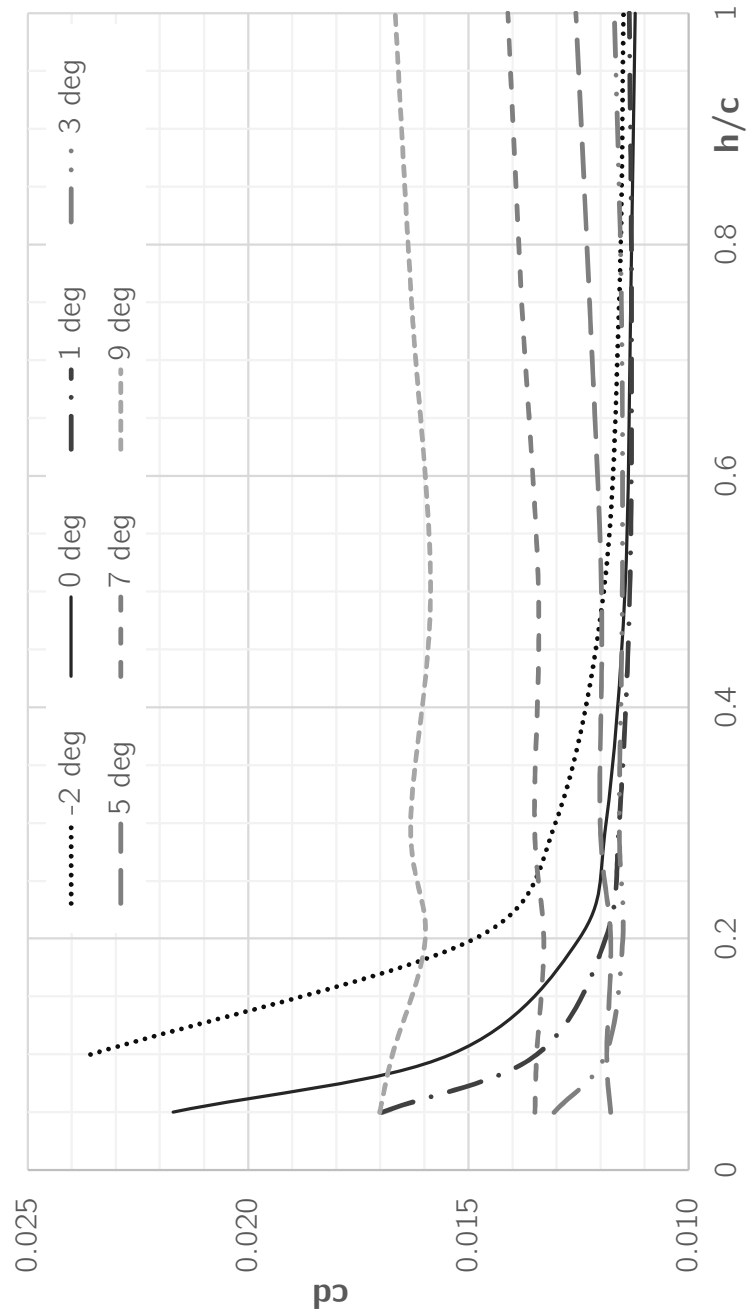


Figure 3-24 Drag coefficients at varying heights above ground for NACA 25112

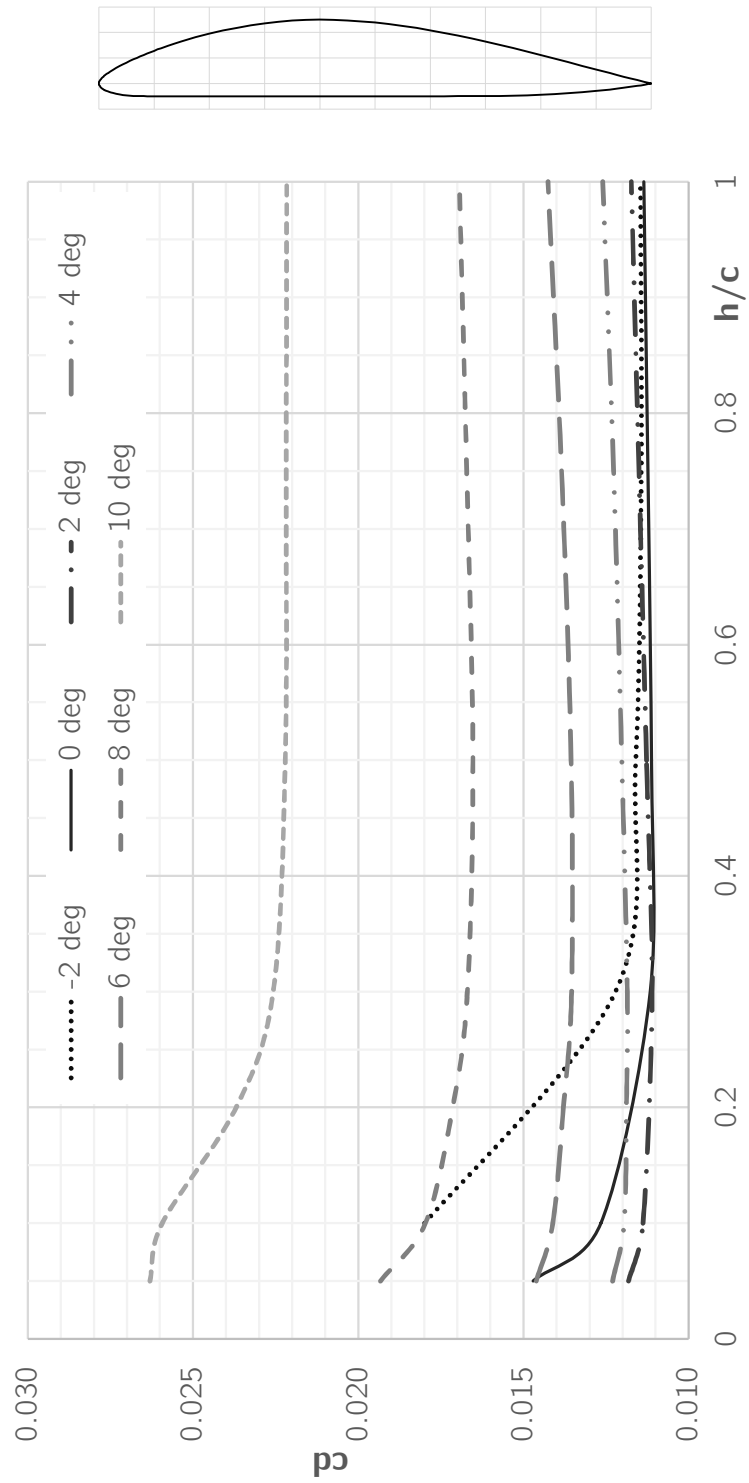


Figure 3-25 Drag coefficients at varying heights above ground for DHMTU 10-40.2-10.2-60.21.5

3.3 Experimental Aerodynamics

The experimental section of this work consisted of physical testing of a model wing, towed in an incompressible fluid, in order to physically validate the aerodynamic characteristics of an unconventional wing profile suitable for use IGE. The profile tested was the novel DHMTU 10-40.2-10.2-60.21.5. There has been no previous experimental data for this airfoil released into the public domain.

Forces were measured using a transducer mounted above the wing, out of the water. Calibration and sensitivity testing of the transducer is described in Section 2.3.3. As pressure taps were not able to be used, detailed flow patterns weren't discernible. However, as this profile was analysed in the 2D CFD programme, it was assumed that the pressure distribution and pitching moment would be similar to the CFD values if the lift forces were also similar.

Drag resulting from the immersed sections of the towing rig and surface wavemaking of the support arms were estimated to be an order of magnitude greater than that of the parasitic and induced drag of the lifting foil. As such, the drag values will not be reported here.

Test runs were carried out at three Reynolds numbers: 450 000, 750 000 and 1 050 000. The highest Re corresponded to the highest speed the tank carriage could safely tow the wing, and was also the Re at which the CFD analysis was run. The following plots, Figure 3-26 through Figure 3-28, show the mean lift coefficients measured across the tested heights for each angle, with error bars indicating +/- one standard deviation.

There is a slight variation with Re across most of the angles, although this is most pronounced in the -4° results. It is not clear if this is fundamental behaviour or experimental error due to unsteady flow characteristics at this extreme nose-down angle. Note also that at this angle the direction of the force across all heights is downwards, i.e. suction towards the bottom surface.

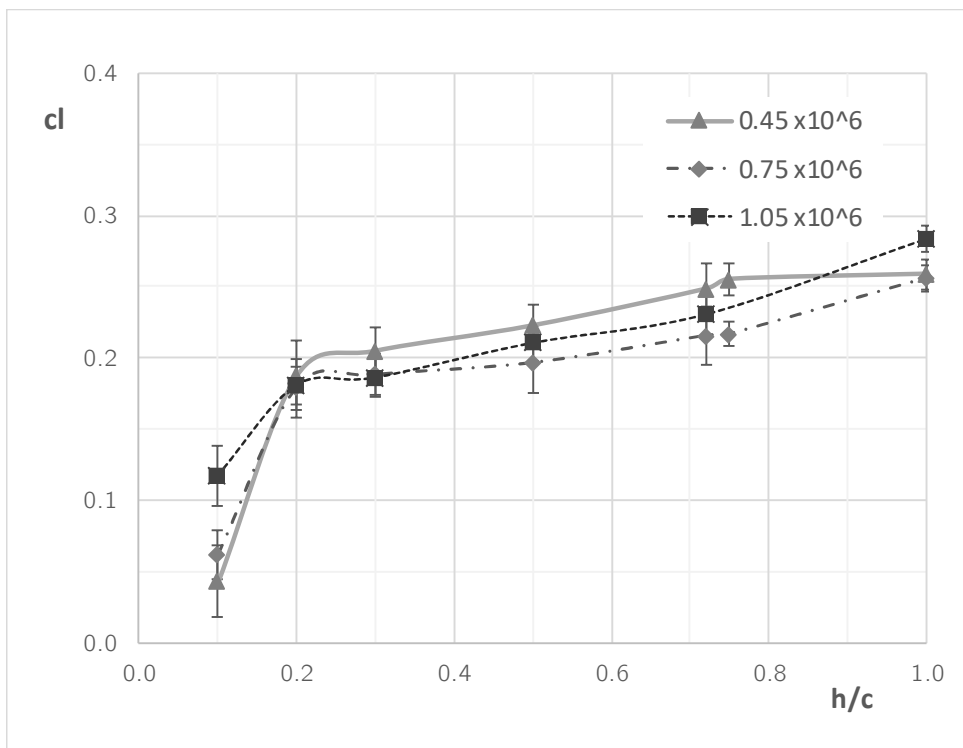
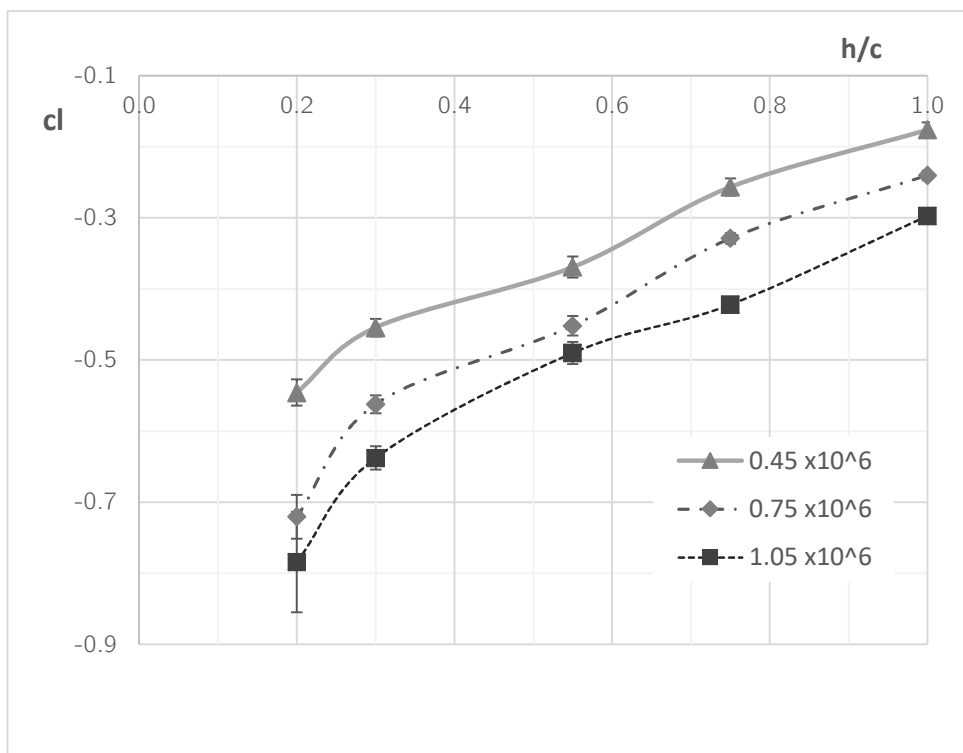


Figure 3-26 Comparison of lift coefficients at varying Reynolds numbers and heights above ground for DHMTU profile at -4° (top) and 0° (bottom)

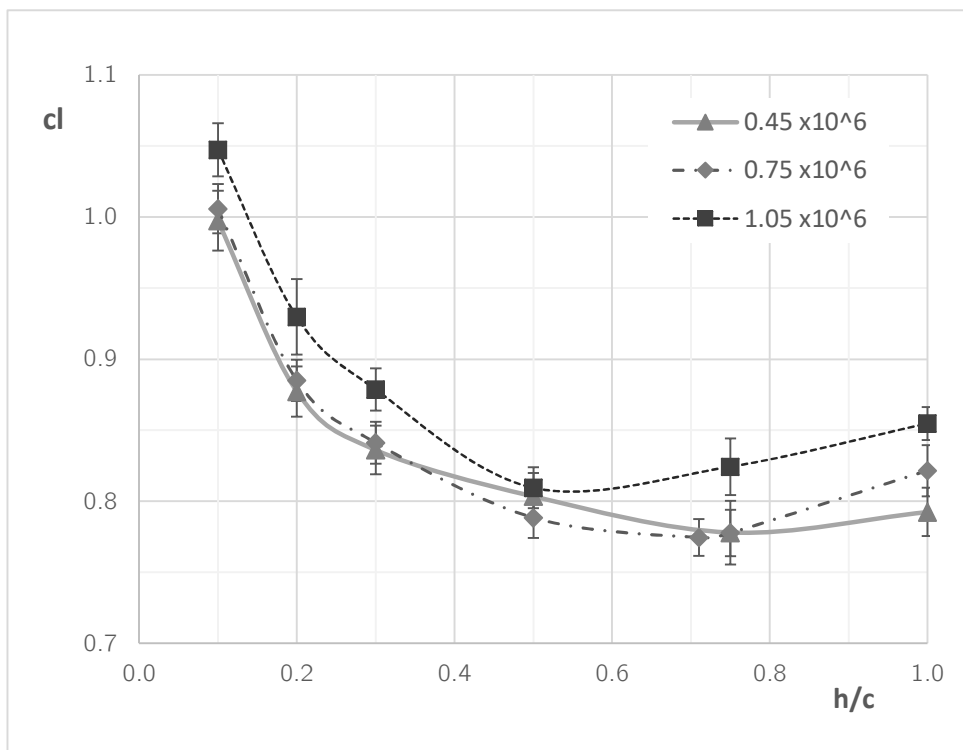
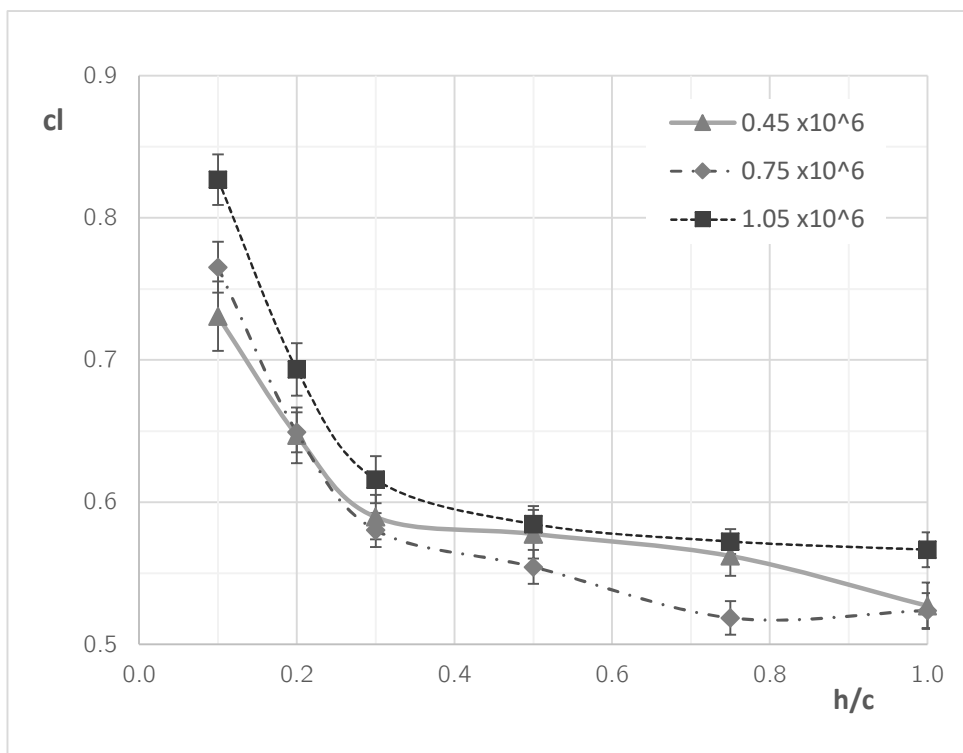


Figure 3-27 Comparison of lift coefficients at varying Reynolds numbers and heights above ground for DHMTU profile at 4° (top) and 8° (bottom)

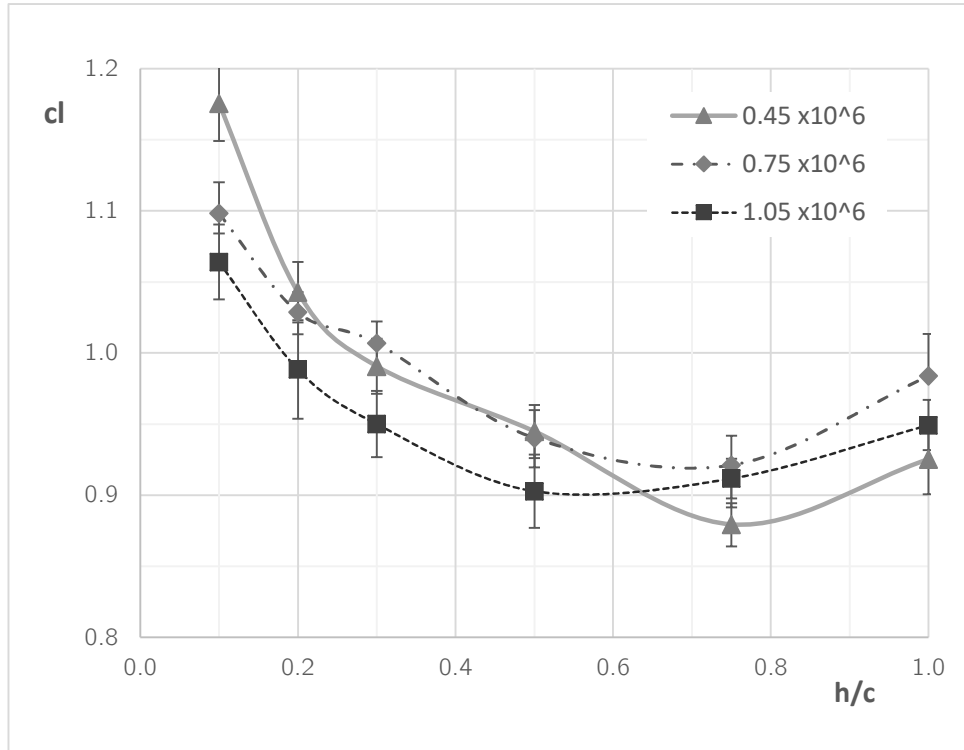


Figure 3-28 Comparison of lift coefficients at varying Reynolds numbers and heights above ground for DHMTU profile at 12°

The following figures show how the changes in Re affect the lift forces with respect to angle (Figure 3-29 through Figure 3-31) and height (Figure 3-32 through Figure 3-34). The experimental data is presented in the same manner as the CFD data for all of the profiles in Section 3.2. In this format, the experimental data can be compared to the numerical CFD data for this profile.

As the three plots in each of the figures are quite similar, it can be concluded that there is not a strong dependency on Re for the tested velocities.

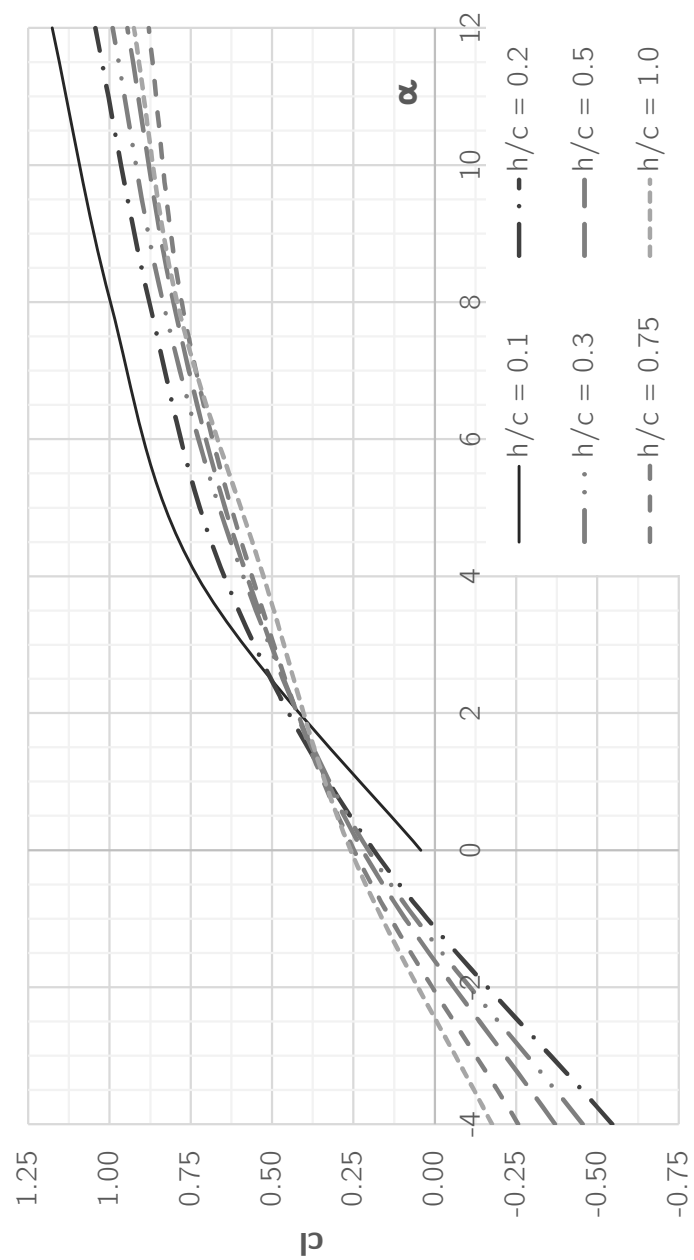


Figure 3-29 Comparison of measured lift coefficients at varying angles of attack for $Re = 0.45 \times 10^6$

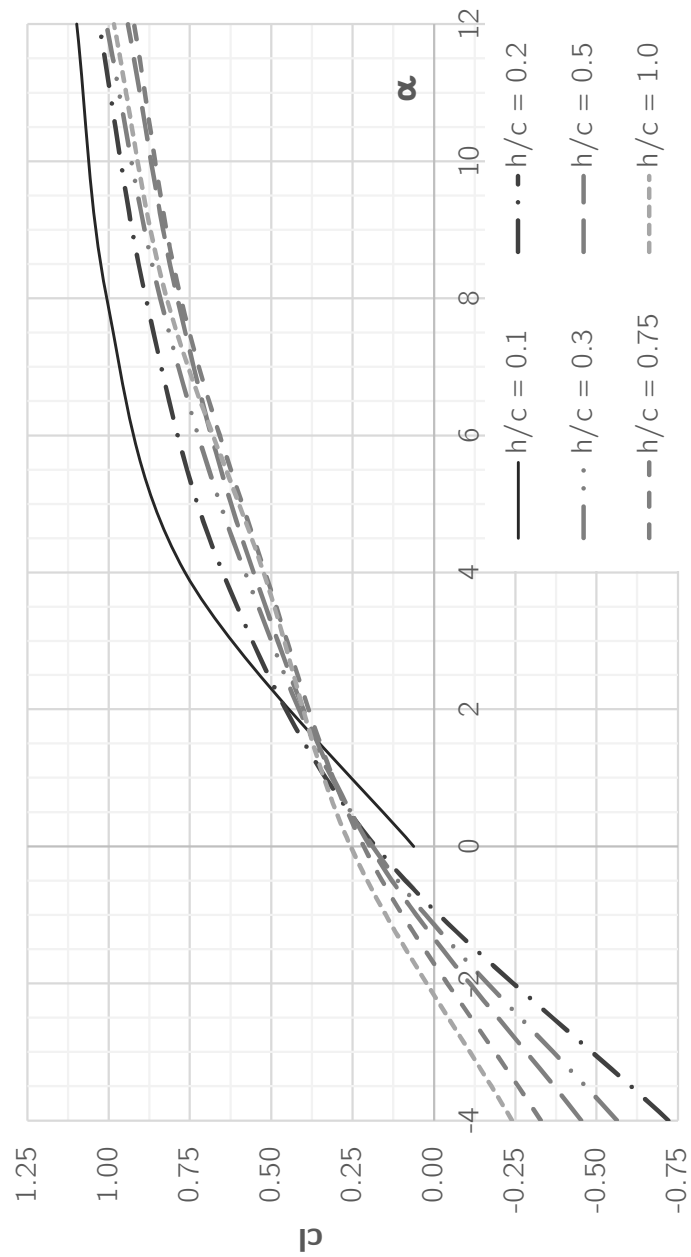


Figure 3-30 Comparison of measured lift coefficients at varying angles of attack for $Re = 0.75 \times 10^6$

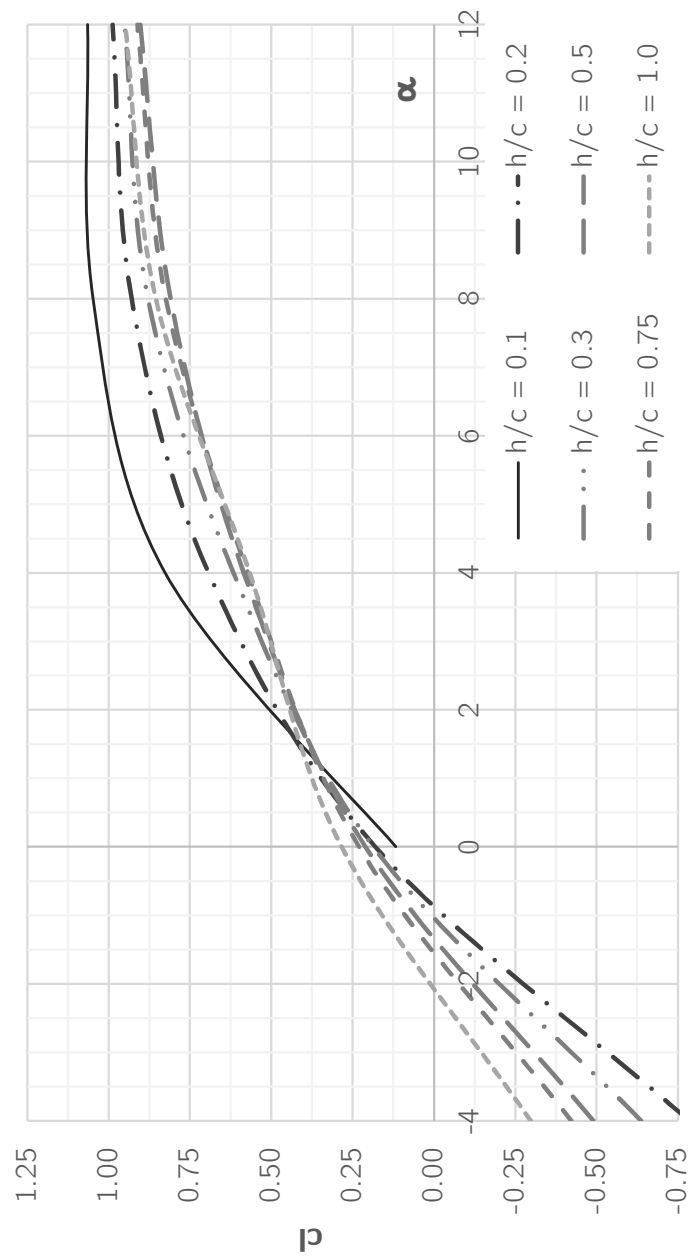


Figure 3-31 Comparison of measured lift coefficients at varying angles of attack for $Re = 1.05 \times 10^6$

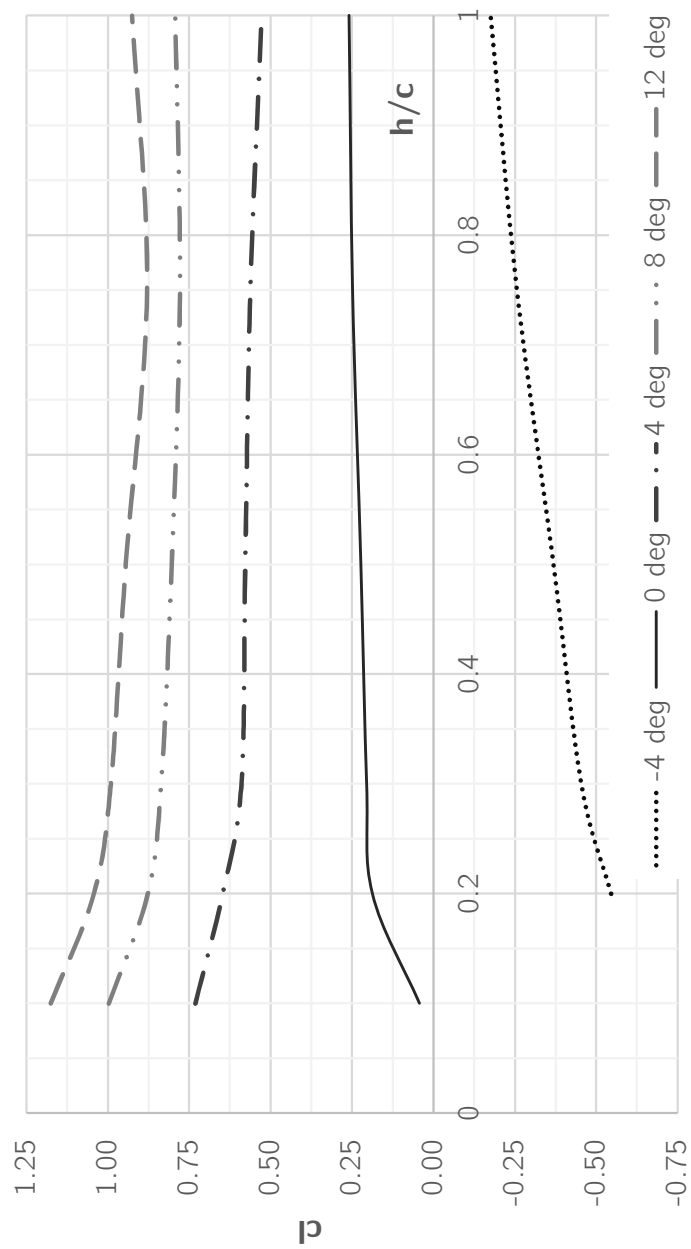


Figure 3-32 Comparison of measured lift coefficients at varying heights above ground for $Re = 0.45 \times 10^6$

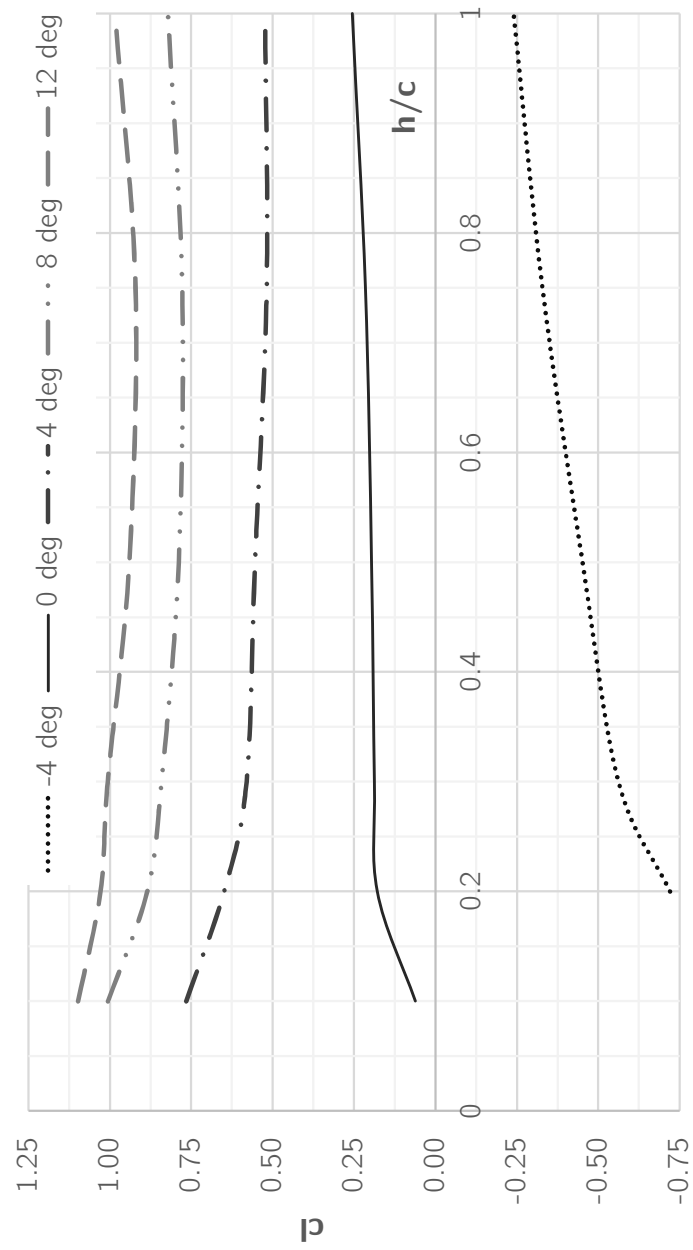


Figure 3-33 Comparison of measured lift coefficients at varying heights above ground for $Re = 0.75 \times 10^6$

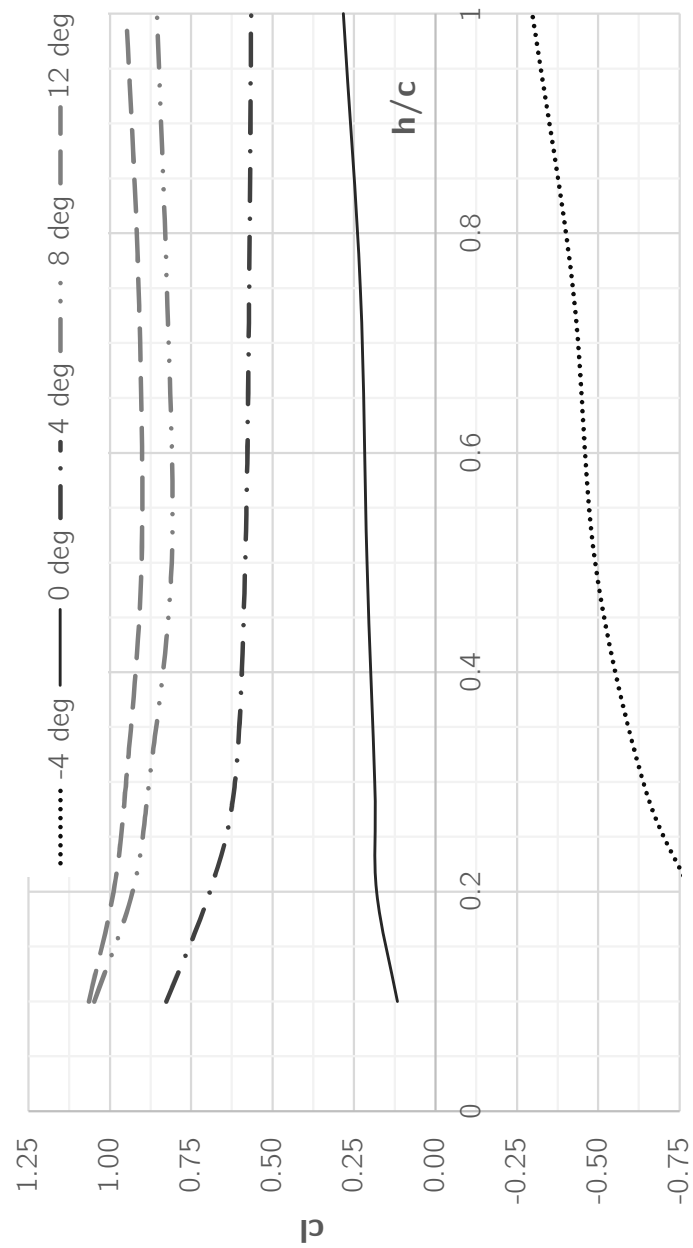


Figure 3-34 Comparison of measured lift coefficients at varying heights above ground for $Re = 1.05 \times 10^6$

4 Discussion

In keeping with the format of the previous sections, discussion of the results of the experimental and computational work will be divided into their respective categories. Again, the hull model testing will be presented first, followed by the computational aerodynamics and finally wing model testing.

4.1 Hull Model Testing

A prediction line for the total resistance across the tested speed range was computed for the 100% displacement condition prior to testing, to be used as a comparative benchmark. The estimate was based upon slender body theory, characterised as a first principles potential flow approach to predict the far-field wave pattern. The intention was not to predict exact performance *per se*, but to gauge the probable loading upon the test rig, towing carriage and associated equipment. As the model would be fully constrained, it was not clear how close this prediction would correspond to the test runs.

Slender body approximations assume the characteristic length of a body in the direction of the fluid flow is much larger than the dimensions in the other two orthogonal directions. Ideal flow around the body is simulated by placing sources of varying strengths along the centreline in the forward part of the body, with sinks in the after part, such that the sum of their total strength is zero. Total force on the body can be derived through integrating the local forces along the length of the body at a finite number of thin transverse strips.

Michell's thin-ship theory developed this methodology to determine wave resistance for thin ships, i.e. those following the same assumptions as for a slender body. Therefore, this method can be used in cases where the vessel length is much greater than the beam and draught, to assess calm water 2D flow around the vessel. Although this method assumes potential flow, viscous effects are captured through a form factor correction to the skin friction drag, which can be calculated from the geometrical wetted surface area at a given displacement.

Analytical methods for performance prediction of high-speed hullforms were found to be very far out of range, as none were appropriate for speeds in excess of $Fn_L > 1$ (Insel and Molland, 1992; Armstrong and Schmieman, 2005). Instead, an open-source research code called Michlet that uses the Michell integral as the basis for calculating vessel resistance and far-field wave elevation was used for the prediction. Transom stern effects and boundary layer thickness effects have been included in the code.

Also a possibility was using CFD methods for resistance prediction, that could also take into account dynamic loads to provide force and moment data in the vertical direction. This was not feasible in the present work for a number of reasons. Firstly, it was essential that the prediction method should be simple, easy to replicate and relatively quick to set up and run. As no CFD tool was available, the time and effort to build a reliable routine would have been prohibitive. Secondly, there were no known cases for verification and validation of computational results. Using hull shapes that differed significantly or operated at vastly different speed regimes would not be appropriate to confirm accuracy of results or method. Finally, the complexity of a rigorous 3D model, ensuring appropriate boundary conditions and resolution of the boundary layer, etc. merits its own project focussed on developing such a tool that could be used with an appropriate degree of confidence.

The contribution of viscous effects was estimated using a form factor multiplier on the frictional resistance of the static wetted surface area, as documented in the ITTC 1957 method. Although this form factor can be shown to vary with increasing speed, careful selection of a single average value for the entire range was expected to have a maximum error of +/- 5% (Molland, Wellicome and Couser, 1994).

Standard model test data analysis consists of deconstructing the measured drag into component parts that can be calculated at model scale and full-size (friction), estimated to be proportional to friction drag and the same for geometrically similar forms (viscous) and then left with a residuary component that is assumed to be a function of wavemaking, in the absence of any other external forces, e.g. air resistance, that is then scaled up before the component parts are reconstructed for the full-size estimate (ITTC, 2008b).

This procedure was not carried out in this case for two main reasons: firstly, this testing programme is fundamental research without a specific full-size target in mind, and second, the extreme speed range covered is highly unusual for marine applications and it is not clear if standard procedures would even be appropriate. Therefore, the data was non-dimensionalised and qualitatively assessed as follows.

The estimated prediction line has been plotted alongside the measured test results as shown in Figure 4-1. The correlation is quite good until the highest speed runs (around $F_{NL} \geq 1.9$, which corresponded to 10 m/s at model scale), although the prediction is considerably flatter with fewer humps and hollows. The estimated line is slightly over-predicting up to this point.

At this stage of development, the actual performance of this hull at these speeds and trim angles is not exactly known. By comparing two very different methods, *viz.* potential flow code vs. experiment, the agreement of results can indicate mutual validation. That is, numerical and experimental results that are qualitatively in agreement are either likely to be substantively correct or the methods must share the same errors. The risk of similar errors is greatly mitigated by using two disparate techniques, as done here.

There appears to be a dip in the measured data between $0.75 \leq F_{NL} \leq 1.65$. The reason for this was not readily apparent but it is likely due to the model being restrained in heave (it was constrained in all degrees of freedom). If left free-to-heave, it is possible that dynamic effects would lift the hull sufficiently to account for this reduction. Alternatively, the computed prediction line may not have captured the correct wave pattern and effectively averaged out these effects. A more comprehensive testing programme with different constraints would be advisable, but was not within the scope of this work.

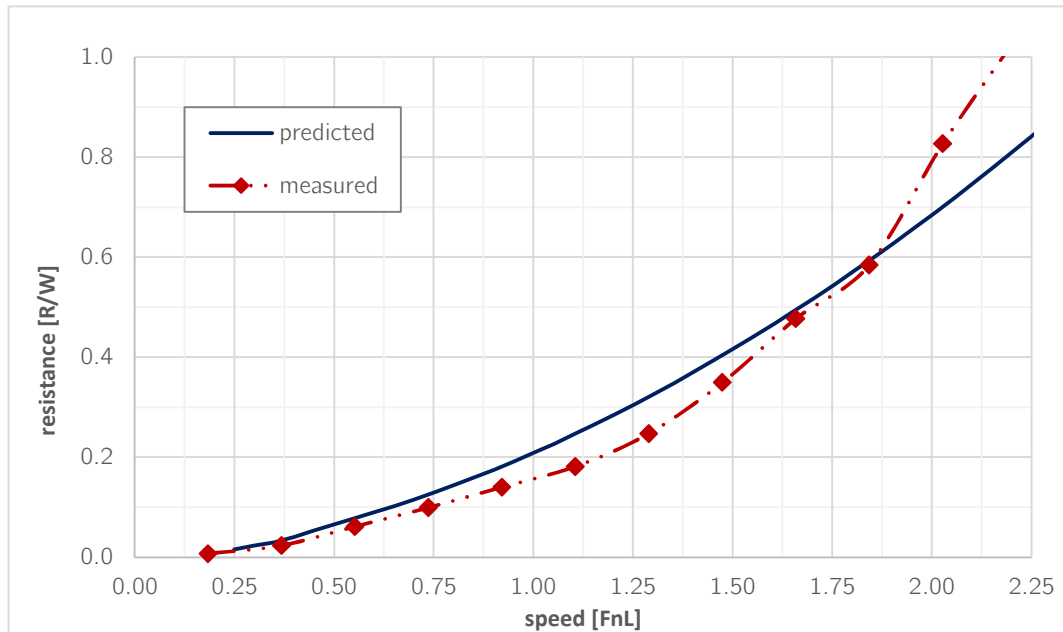


Figure 4-1 Predicted vs measured resistance at full displacement

After checking video footage of the higher speed runs, a significant amount of spray generation and side wetting were occurring. Side wetting can be considered solid water rising up the side of the vessel in a pressure recovery phase, that happens when near-surface water becomes entrained in a wave pattern that travels along with the vessel. Spray generation is very similar but is typically an air-water mixture whose constituent parts can vary from mostly water at the spray root to mostly air at its extremities. This is often seen as a ‘rooster tail’ of spray thrown up from the propeller following a high-speed power boat, as the water surface elevation that has been depressed under the vessel returns to an equilibrium state.

Both spray generation and side wetting require energy for their formation, energy that must come from the vessel propulsion system. Both of these phenomena increase drag on the vessel and consequently power required for a given speed, and are typically avoided in established vessel designs to the extent that it is possible.

In this case, the side wetting was not unexpected as this is one of the primary reasons for hard chine hullforms for high-speed planing vessels. Introducing a chine at the turn of the bilge could be one method to encourage flow separation off of the hull. Spray rails and other hard discontinuities are also typically used for this purpose.

Figure 4-2 shows still images of the spray root and its generation followed by solid-water side wetting during test runs at 12 m/s, for 100% displacement and 75% displacement at 3° of running trim. Figure 4-3 extends this series to include the 25% displacement condition with the other variables unchanged, shown in the upper image.

Markings have been superimposed upon the images to indicate the relevant points. It can be seen that the spray root location does not change significantly with a small reduction of displacement. Side wetting appears to be slightly reduced when comparing the 75% to 100% condition, which is as expected as less water has been displaced and subsequently returns to zero surface elevation.

The location of spray root moves further aft for the 25% condition but again not a large amount. The reason for this is that the rocker in the forward part of the hull results in transverse cross-section areas that increase in breadth and depth from the stem to midship section. Planing hulls that rely on dynamic lift and look to reduce these inefficiencies typically employ prismatic hullforms, such that cross-section areas remain constant for the majority of the length. Deep-V hulls and warped transverse sections that are not prismatic by definition are also used in some craft in order to alter some part of the ride characteristics. Furthermore, a rearward LCG position results in the planing craft trimming around a point much further aft, whereby the trimming moment has the effect of lifting the bow sections clear of the water so that the spray root occurs much further aft. This dynamic trimming does not occur in a fully-constrained model.

Figure 4-3 also presents a still image of spray generation as seen from astern. The follow-on work for testing this type of hullform should included geometrical features to reduce this amount of spray and energy loss.

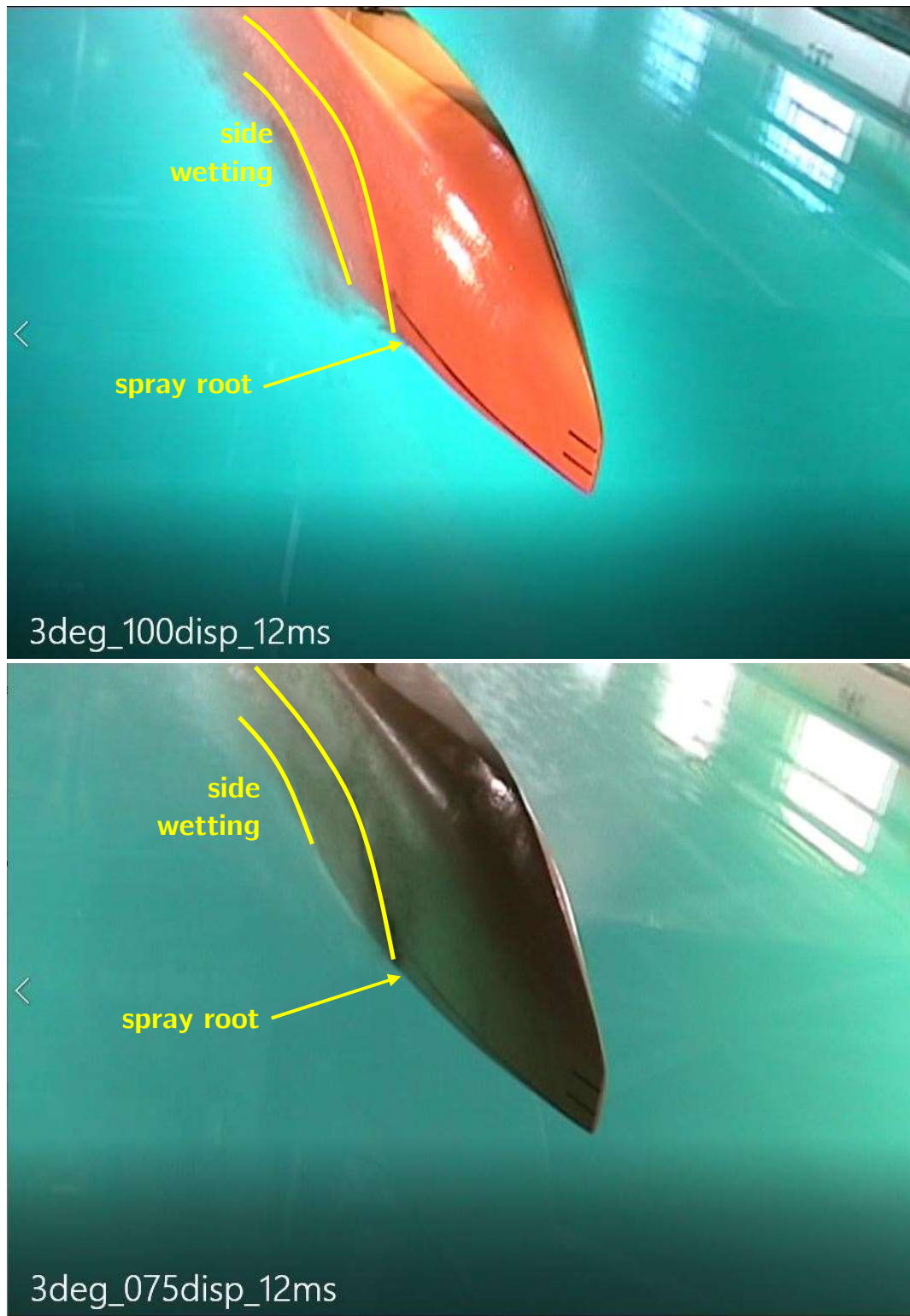


Figure 4-2 Spray generation at 12 m/s, for 100% disp. (upper) and 75% disp. (lower)

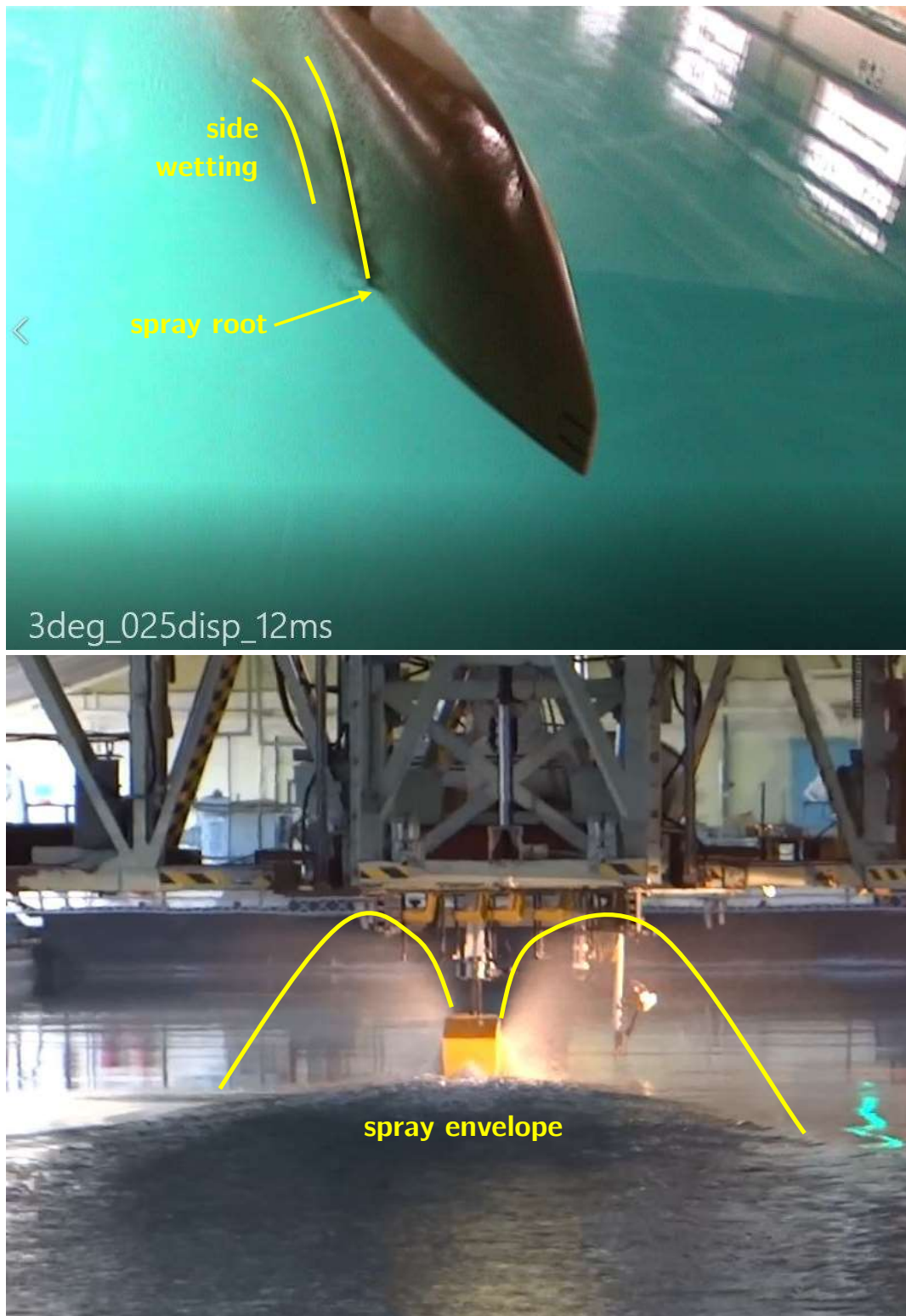


Figure 4-3 Spray generation at 12 m/s, for 25% disp. (upper) and seen from astern (lower)

The next step of the analysis was to compare the effect of a small trim angle of 3° to the 0° level trim condition. Under typical conditions it would be expected that a small trim angle would decrease drag, perhaps mainly due to the contribution of the vertical lift component of an angled plane. However, as the model was constrained in heave, this did not occur.

Figure 4-4 shows the measured drag at 0° compared with 3° for the full displacement condition and at 80% and 50%, respectively from top to bottom. These runs were carried out to assess how drag is affected as the vehicle rises due to aerodynamic alleviation. Interestingly, until the model is unloaded to 50%, the differences between the two trims are minor. Note that the upper plot is still showing the effect of the side wetting at $Fn_L \geq 1.8$ in the 0° condition.

As the hull lines show a relatively flat bottom the effective entry becomes quite bluff, similar to a flat plate, and as viscous drag is the dominant component there is not much difference between the two.

Resistance appears to be higher in the 50% displacement condition than for the heavier configurations but only due to normalisation to the tested weight. In absolute terms, resistance diminishes rapidly as unloading occurs as shown in Figure 3-2 for 0° trim and Figure 3-5 for 3° .

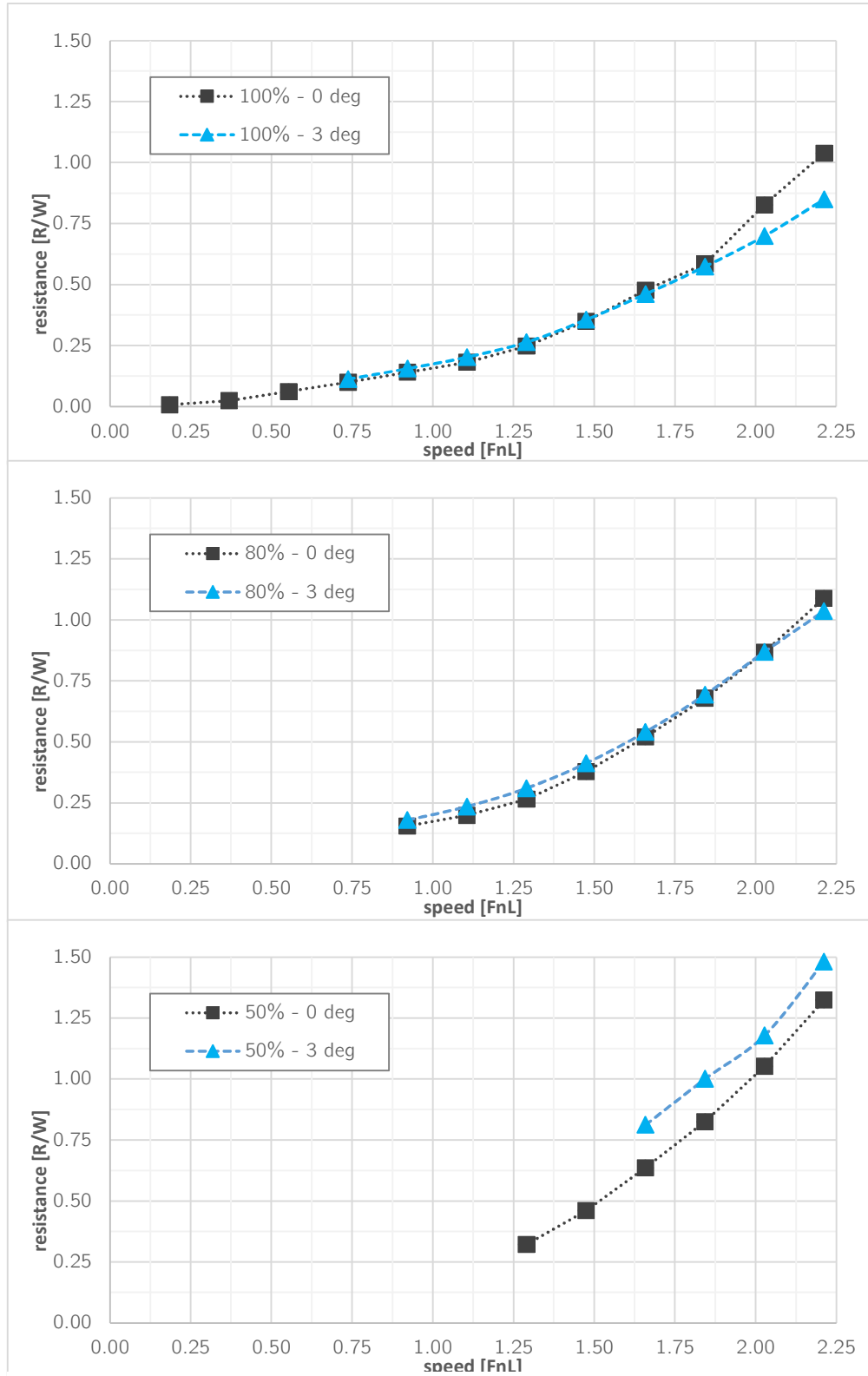


Figure 4-4 Model resistance comparison at 0 deg & 3 deg for 100%, 80% & 50% displacement (from top)

WIG craft generally experience a critical velocity during take-off, a point at which the aerodynamic forces alleviate the hydrodynamic forces, resulting in an apparent reduction in vessel displacement, such that the vehicle drag continues to reduce whilst speed increases (for constant power input) which further alleviates the hydrodynamically-supported weight. The craft can effectively hop across the resistance curves until it is fully airborne, as depicted in Figure 4-5.

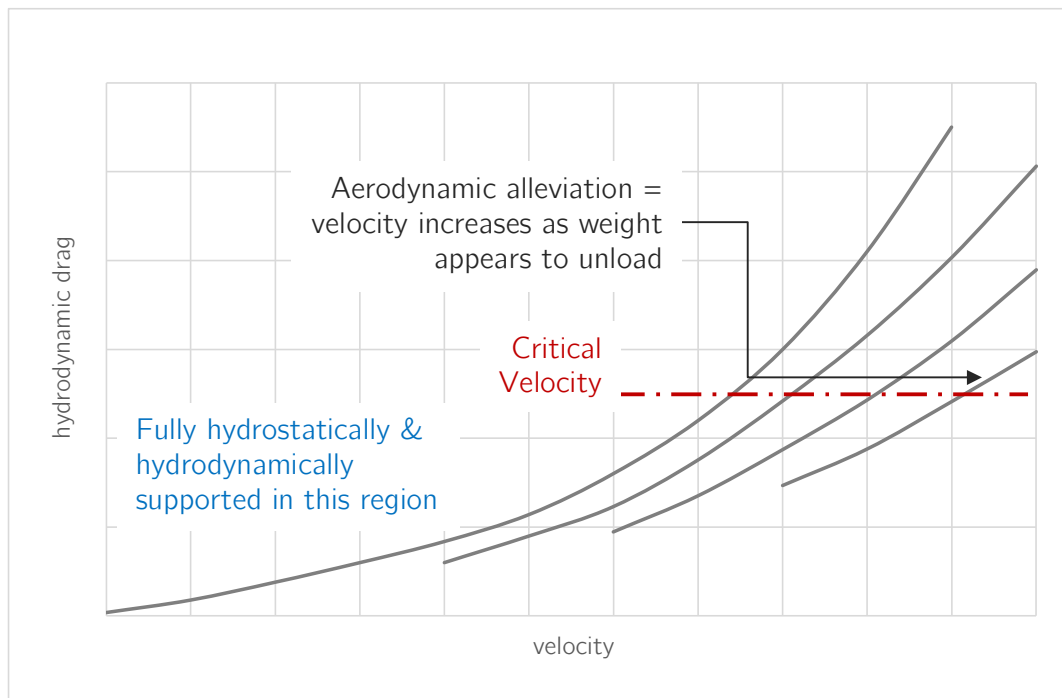


Figure 4-5 Diagram of aerodynamic alleviation

4.2 CFD Database

4.2.1 Comparison of Profiles

Each of the profiles were analysed over a range of normalised heights from 0.05 to 1.0, and angles of attack from -2° to 9° for the NACA sections and from -2° to 10° for the DHMTU section, as this range should be representative of the likely operating conditions. Forces and moments were measured about the trailing edges and converted to coefficient form based on freestream flow velocity and density.

The observed trends were quite consistent over the tested range, with the NACA 4412 producing greatest lift for a given angle over most of the height range, followed by the DHMTU profile, then NACA 25112. Figure 4-6 shows typical lift curves for each of the profiles as a function of height. This angle, $\alpha = 3^\circ$, is representative of the general trends and comparative differences between the profiles.

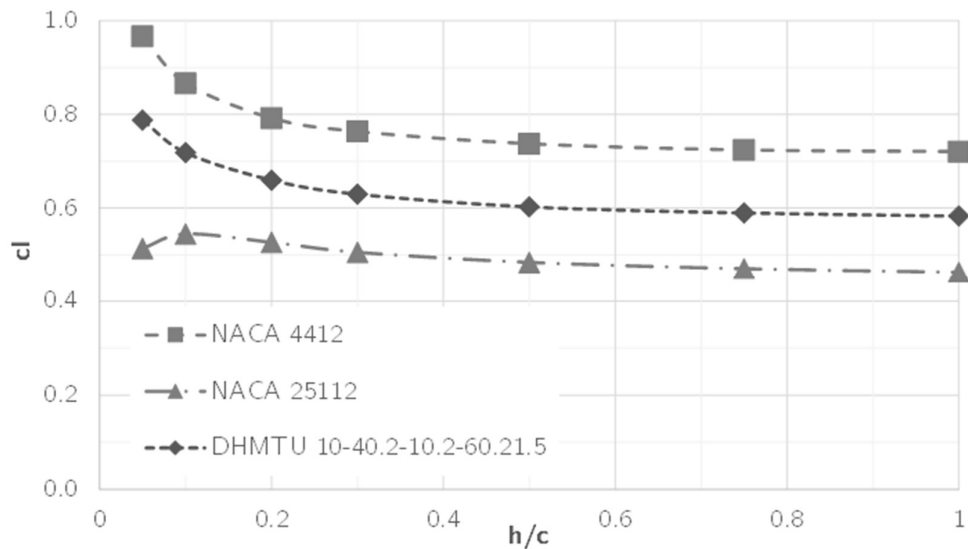


Figure 4-6 Lift coefficient comparisons of the three profiles, $\alpha = 3^\circ$

The NACA 25112 at this angle displays a reduction in lift at the lowest height ($h/c = 0.05$). This must be considered an unfavourable characteristic for GE vehicles as this loss of lift would cause the craft to drop towards the ground or water surface. This suction effect in EGE is similar to that seen with the 4412 profile at $\alpha = 1^\circ$ (see Figure 3-11) although the lift subsequently becomes positive for the 4412 at smaller AoA, from around $\alpha = 3^\circ$ and higher. This phenomenon of negative lift in EGE is thought to be due to convergent-divergent flow when in close proximity to the ground and is discussed in Section 3.2. It should be noted that this behaviour in EGE is not the same as the experimental results described in Section 2.2.2.1 that showed a general trend of decreasing lift across the entire GEZ, which does not readily agree with any known data of this profile.

Interestingly, the DHMTU profile also began to experience loss of lift around $\alpha = 1^\circ$ as EGE was approached, even though the flat bottom was intended to reduce negative effects at very low heights. The severity of the lift drop-off is reduced indicating a more gradual resultant change in vessel height. The negative angles, i.e. $\alpha = -2^\circ$ and below, should be avoided under any circumstance. This can be achieved by mounting the wing on the vehicle with an angle of incidence that keeps the AoA in the positive range. At $\alpha = 2^\circ$ the lift increase is positive but small and continues to grow throughout the tested range.

Above these critical angles, all of the lift curves continued to rise as the ground was approached. Figure 4-7 shows each profile at a different angle, one that results in comparable lift production, as shown by the c_l values in the upper plot. The DHMTU profile required an angle around 1° greater than the 4412 to produce similar lift, while the 25112 required an increase around 2° greater. This trend was fairly consistent across the range of angles.

Note that although the c_l values converge as height is reduced, the 4412 maintains its c_l around 0.05 higher than the other two profiles as free-stream conditions are approached. This would correspond to an effective increase of approximately $\alpha = 0.5^\circ$ following a conventional lift-curve slope in thin airfoil theory. The result is that reflexed profiles would need to increase AoA slightly as flying height is increased to maintain equal lift. This is common procedure for WIG craft and this small difference would likely be

negligible. Another way of viewing this result is that reflexed profiles experience greater lift benefit in the GE zone relative to their OGE performance.

The generated moments were compared at these angles, as shown in the lower plot. The 25112 produced the greatest positive (nose-up) moment across all heights. This is the characteristic that allows the craft to reduce or eliminate tail control surfaces and make it ideal for flying wing designs in unbounded flow conditions. However, the loss of lift near the ground for moderate angles renders this profile unsuitable for GE use unless kept to $\alpha \geq 5^\circ$.

The DHMTU profile also generated a greater positive moment than the 4412, although less than the 25112. In EGE the moment is approximately midway between the two NACA profiles, which is where a nose-up moment is most needed. Due to the effect of ram pressure in this zone, nose-down moments are magnified requiring control input to maintain attitude.

Based upon these results, the DHMTU profile seems well-suited for its intended use IGE. The performance over the range of heights and angles was more consistent than the other two profiles, not suffering from severe loss of lift in EGE, and the small but significant increase of nose-up moment would result in a smaller tail surface required to satisfy static stability requirements.

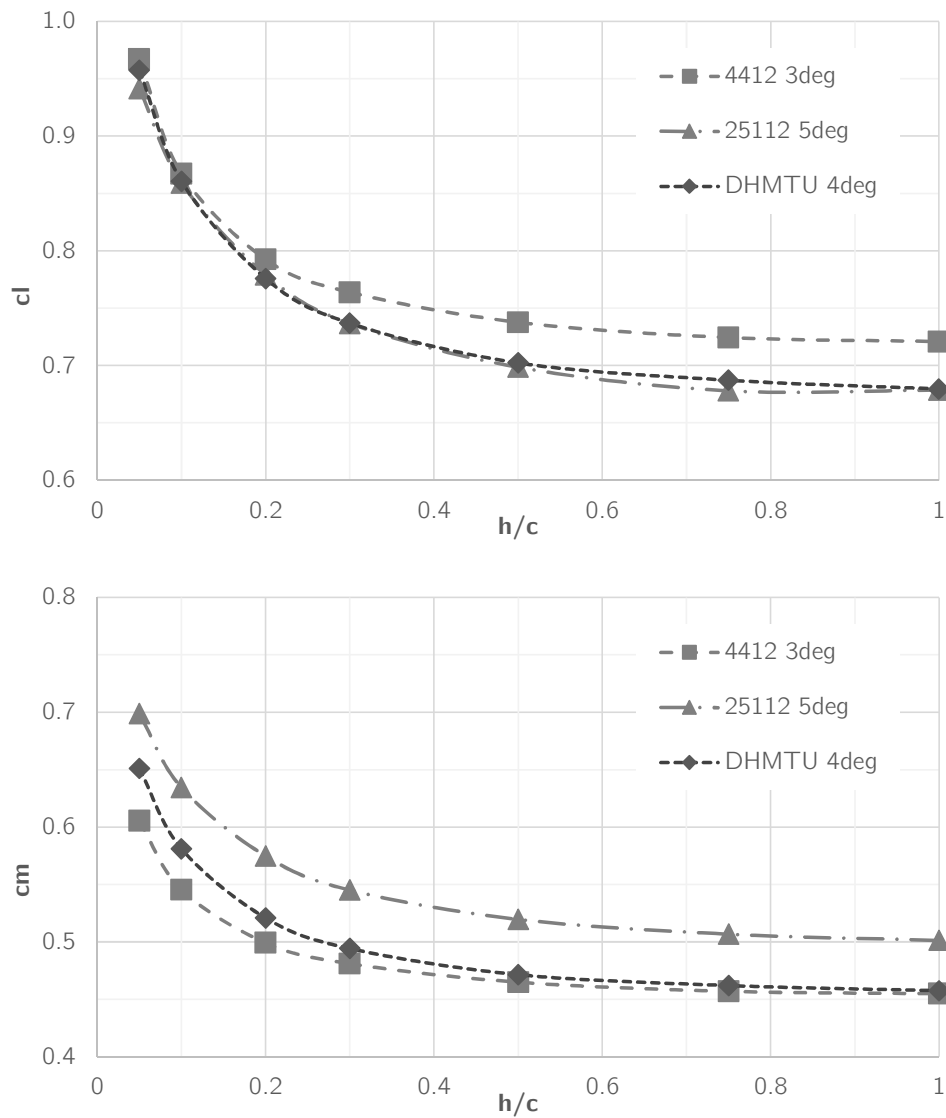


Figure 4-7 Lift (upper) and moment (lower) coefficients over the height range for the three profiles at comparative angles; note that moments are taken about the trailing edge

4.2.2 Lift/Drag Efficiency

As described in Section 3.2.1 and summarised in Figure 4-6, the NACA 4412 achieves higher c_l for a given AoA when compared to the NACA 25112 and DHMTU profiles. This does not give a true indication of its performance IGE though, as consideration of moment magnitude and direction has already been highlighted, but additionally assessment of the profile drag for a given c_l indicate aerodynamic efficiency for any combination of angle and height. This efficiency is expressed as a ratio of c_l to c_d , thereby giving lift per unit drag (L/D).

As shown in the upper plot of Figure 4-8, the 4412 profile produces the highest efficiencies of the three profiles. For angles $2.7^\circ \leq \alpha \leq 7.3^\circ$, the 4412 achieves $L/D \geq 80$ and even $L/D \geq 90$ between $3.3^\circ \leq \alpha \leq 5.8^\circ$ for the lowest height, $h/c = 0.05$. When height is increased to $h/c = 0.1$, this profile still achieves $L/D \geq 80$ between angles $3.5^\circ \leq \alpha \leq 7.4^\circ$.

The 25112 profile also reaches $L/D \geq 80$ for $h/c = 0.05$, but only when $\alpha > 5^\circ$. There is a marked drop-off in efficiency for shallower angles than this for both $h/c = 0.05$ and $h/c = 0.1$. The 4412 profile also displays this tendency, as although impressive maximum L/D ratios are reached over a small range of angles, once AoA drops below this range a steep decline occurs.

Rapid changes in L/D ratios are not conducive to stable operation as decreasing L/D implies greater propulsive thrust would be required to maintain a given speed and corresponding lift force to maintain flying height. Characteristics such as moderate gradients and similar trends across the range of heights would indicate a profile suitable for operating in the GEZ.

The DHMTU profile shows predictable transitions between plots for varying heights and moderate changes in L/D as AoA varies. Maximum L/D is lower than both NACA profiles at around $L/D_{\max} \approx 80$ but qualitatively shows a fair distribution without unpredictable discontinuities. As such, this indicates that the DHMTU would be an ideal profile at typical operational angles and heights in the GEZ between $2.5^\circ \leq \alpha \leq 9.0^\circ$.

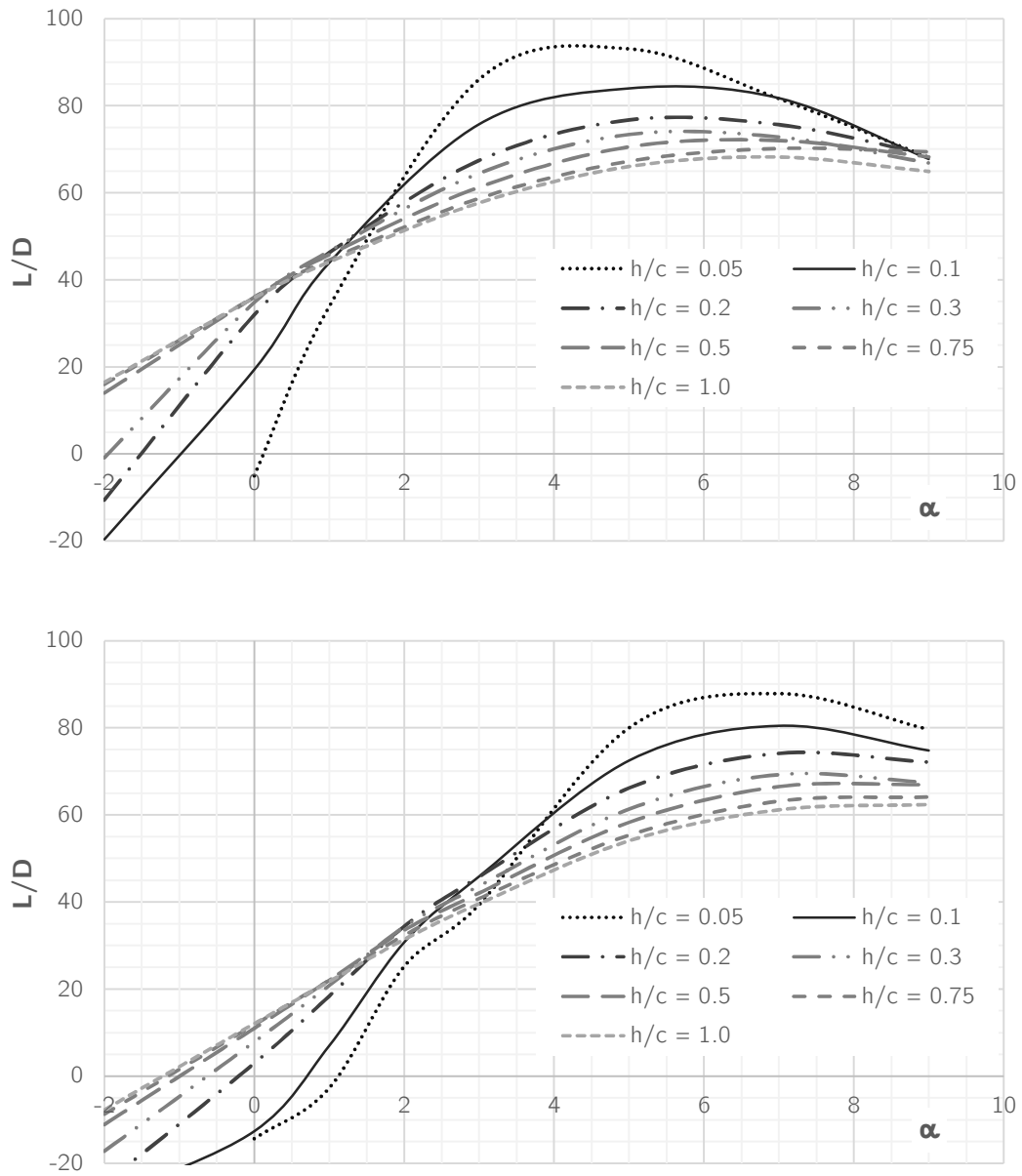


Figure 4-8 Aerodynamic efficiency IGE for NACA 4412 (upper) and NACA 25112 (lower)

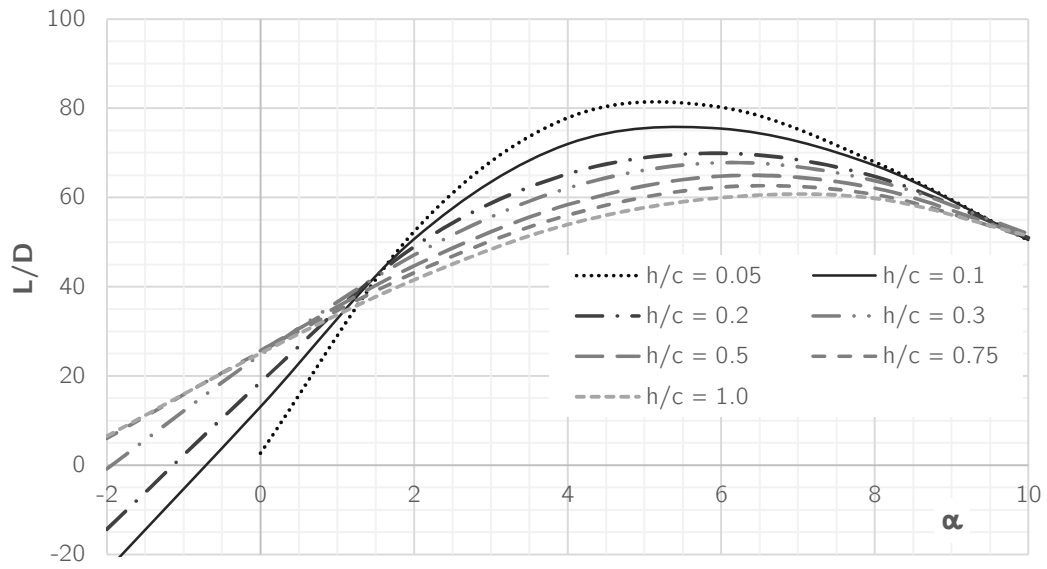


Figure 4-9 Aerodynamic efficiency IGE for DHMTU 10-40.2-10.2-60.21.

4.2.3 Determining Aerodynamic Centres

As with any force and moment system due to a distributed load on a body, the resultant force can be placed at any point on the body as long as the value of the moment about that point is also given. During the early days of researching aerodynamic properties of various airfoils, the National Advisory Committee for Aeronautics reported orthogonal lift and drag forces, and moment characteristics about the so-called aerodynamic centre, defined as the one point on the airfoil about which the aerodynamically generated moment is independent of AoA (Anderson, 2001).

In free stream conditions, AoA is directly proportional to lift up until the onset of stall, therefore the definition of aerodynamic centre implies that point along the chord where the moment coefficient remains unchanging irrespective of lift coefficient.

As summarised in Section 1.3.1.2, GE literature refers to this classical aerodynamic centre with respect to AoA as Aerodynamic Centre in Pitch (ACP) and defines a similar point with respect to height above ground as Aerodynamic Centre in Height (ACH). Stated slightly differently, the ACH should be a point along the chordline about which the moment coefficient is independent of lift coefficient as the height above ground is varied.

The raw moments from the CFD models were measured from the trailing edge as that was the most convenient datum point and corresponds the Russian/Soviet method for calibrating height measurements. These moments were then transformed to determine the point where the moment was unchanging across the range of angles. The following formula was used for the moment transforms:

$$C_{Mac} = C_{Mte} + C_L x_{ac} \quad (4-1)$$

where C_{Mac} = moment coefficient at AC, C_{Mte} = moment coefficient at TE,

C_L = lift coefficient and x_{ac} = position of AC

In order to determine the ACP for a given profile, each of the individual x_{ACP} positions were calculated across the height range, along with the corresponding C_{Mac} values. For ACP to be in a single non-moving location, the x_{ACP} and C_{Mac} should be independent of height and not vary across the height range.

Similarly, to determine ACH each individual x_{ACH} position was calculated across the AoA range, along with the corresponding C_{Mac} values. Again, for ACH to be a single location the x_{ACH} and C_{Mac} should be independent of AoA and not vary with α .

The details of how these values were calculated for each of the profiles and plots of performance characteristics are provided in Appendices 8.7 through 8.9.

4.2.3.1 ACP & ACH for NACA 4412

Figure 4-10 shows the ACP (upper plot) and ACH (lower plot) locations for the NACA 4412 profile. At the greatest height, $\bar{h} = 1.0$, the ACP was found at a position of $x/c = 0.755$ from the trailing edge, corresponding very closely to the published OGE value (Abbott and Von Doenhoff, 1959).

The magnitude and nose-down direction of rotation of C_M also matched the OGE value very closely. However, as the wing approached the ground, the position of ACP moved forward until reaching $x/c = 0.710$ at $\bar{h} = 0.05$. There was a corresponding wobble in the C_M line, first increasing slightly before dropping below the OGE magnitude OGE before returning to the baseline value. This small variation around $\bar{h} = 0.2$ may be due to boundary layer interaction affecting the stagnation point and corresponding pressure distribution around the foil.

The lower plot shows that the position of ACH does not appear to settle at any point and continues to move closer to the TE as AoA increases. C_M also continues to increase steadily in magnitude, and after generating a nose-down moment at the lowest angles becomes nose-up at greater angles. In general, a positive moment would be beneficial for self-stability (see Figure 1-15) but becomes much less useful as it does not level off at any particular magnitude.

The significance of this constantly changing ACH position and C_M is that whilst the profile may attain some degree of Static Stability Margin (SSM) at very small AoA, as described and shown graphically in Section 1.3.1.2, this diminishes very quickly as AoA increases. This would necessitate usage of additional control surfaces (e.g. large tail surface) to maintain stability and control IGE.

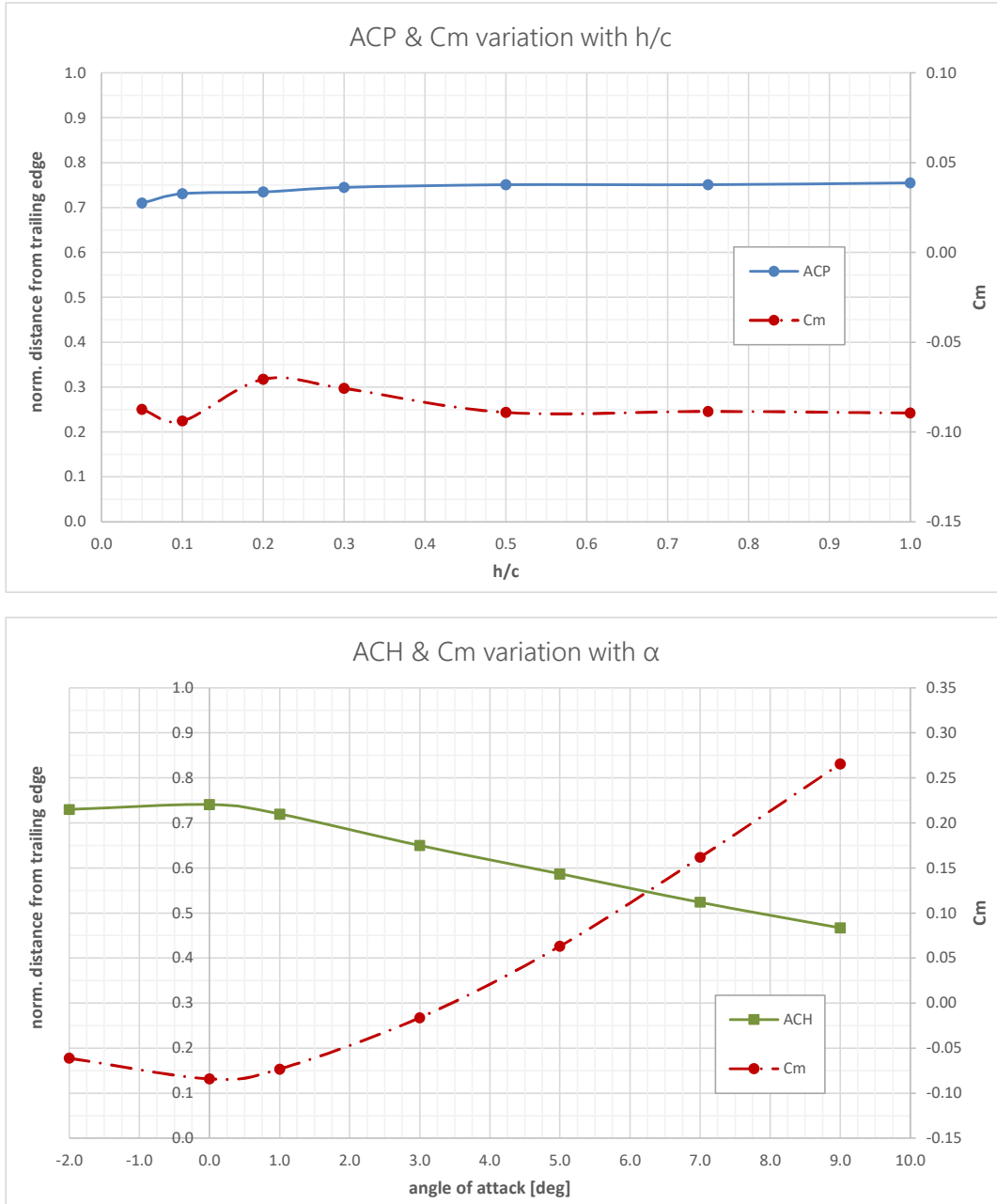


Figure 4-10 Positions of ACP (top) and ACH (bottom) for NACA 4412

4.2.3.2 ACP & ACH for NACA 25112

The same procedure to determine ACP and ACH locations was carried out for the NACA 25112 profile, as shown in Figure 4-11. At the greatest height, $\bar{h} = 1.0$, the ACP was found at a position of $x/c = 0.747$ from the trailing edge, corresponding well to the OGE free stream location around the quarter-chord position. Demonstrating a similar trend to the NACA 4412, the ACP for the 25112 also maintained this position for much of the height range before gradually moving rearwards as height decreased. At the lowest height of $\bar{h} = 0.05$ the corresponding $x/c = 0.602$, approximately 11% further aft than the 4412.

However, a significant difference is that the pitching moment displays a strong nose-up tendency as height decreases. This increase is most prominent in the EGE zone and would require substantial control surfaces to maintain level trim. This is shown quite clearly in the upper plot.

Regarding the position of the ACH and magnitude of C_M , there appears to be a significant anomaly in the range $0^\circ \leq \alpha \leq 3^\circ$. For these angles, the ACH appears to be located behind the wing surface entirely, with a corresponding spike in C_M value. In order to double-check these results, an additional run was carried out at 1.5° to see if there was a computational error or mistake in processing the results. Unfortunately, this trend was confirmed but nevertheless must be considered some type of anomaly. This has been marked on the figure as a region of uncertainty.

The physical meaning of this result is that a strong nose-up moment would be generated between $1^\circ \leq \alpha \leq 3^\circ$ requiring strong control surface input to maintain level operation. Without this input, a sudden nose-up pitching event may become catastrophic if not controlled before the vehicle reaches $\alpha = 6^\circ$ - 7° , at which point the positive moment is steadily increasing again and could result in a nose-over-tail flip.

It is not clear if the behaviour in this range can be attributed to anomalous results due to an error in modelling the underlying physics, e.g. if this profile produces a fundamentally unsteady flow pattern across the indicated angle and height range, such that the RANS modelling would not be able to capture the correct forces and pressure distributions. In order to investigate this, some type of time-dependent modelling, e.g. URANS, could be dedicated to assess the validity of the RANS simulation.

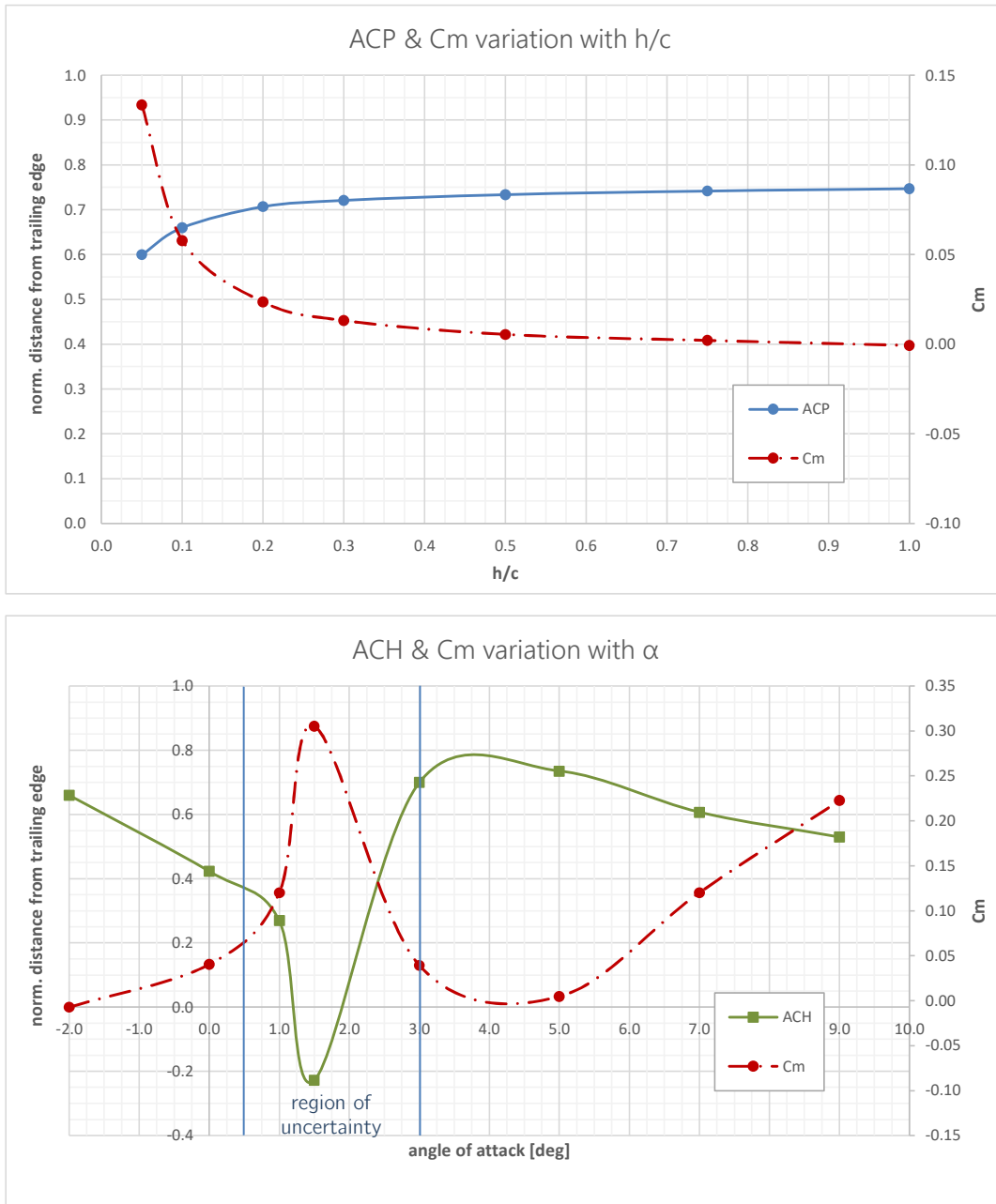


Figure 4-11 Positions of ACP (top) and ACH (bottom) for NACA 25112

In any case, due to this unresolved issue and the previously reported breakdown of lift in the EGE zone at $\alpha \leq 3^\circ$, the NACA 25112 must be considered unsuitable for WIG usage without large control surfaces to mitigate this performance. It is also unclear why this profile would be selected if tail surfaces were to be used, as this reflexed profile was designed to be suitable for tailless aircraft.

4.2.3.3 ACP & ACH for DHMTU 10-40.2-10.2-60.21.5

Finally, the same procedure was carried out for the DHMTU profile, as shown in Figure 4-12. At the greatest height, $\bar{h} = 1.0$, the ACP was found at a position of $x/c = 0.759$ from the trailing edge, slightly further forward than either of the NACA profiles. Also in a similar trend to both NACA profiles, the ACP for the DHMTU maintained this position for much of the height range before gradually moving rearwards around $\bar{h} = 0.3$, followed a sharp movement of approximately 7.5% between $\bar{h} = 0.1$ and $\bar{h} = 0.05$.

At the lowest height of $\bar{h} = 0.05$ the corresponding $x/c = 0.638$ lies between the positions calculated for the two NACA sections, further forward than the 25112 but aft of the 4412. This would indicate that this rearward movement at the lowest heights is likely to be an effect of the reflexed camber line.

The C_M displays a similar trend to the 25112 as the ground is approached of an increasingly positive moment, although the magnitude is not as extreme. However, this change is still approximately 25% - 35% greater than its baseline value and would likely require strong correction to maintain control in EGE.

As the intended characteristic to achieve sufficient SSM, a forward position of ACH is desirable. The lower plot shows how this position changes with AoA. At $\alpha = 2^\circ$, the ACH location is approximately $x/c = 0.873$ from TE. This locates ACH forward of ACP across the entire height range. However, a similar anomaly to the one displayed by the 25112 profile is evident here as well. Between the angles of $\sim 0.5^\circ$ and 3° , the true value of ACH is not clear. There is a definite trend of ACH moving forward from a position of $x/c = 0.502$ at $\alpha = 10^\circ$ to $x/c = 0.698$ at $\alpha = 4^\circ$ but the data points at 2° and 0° indicate that this region is not well defined. This has been marked on the figure as a region of uncertainty.

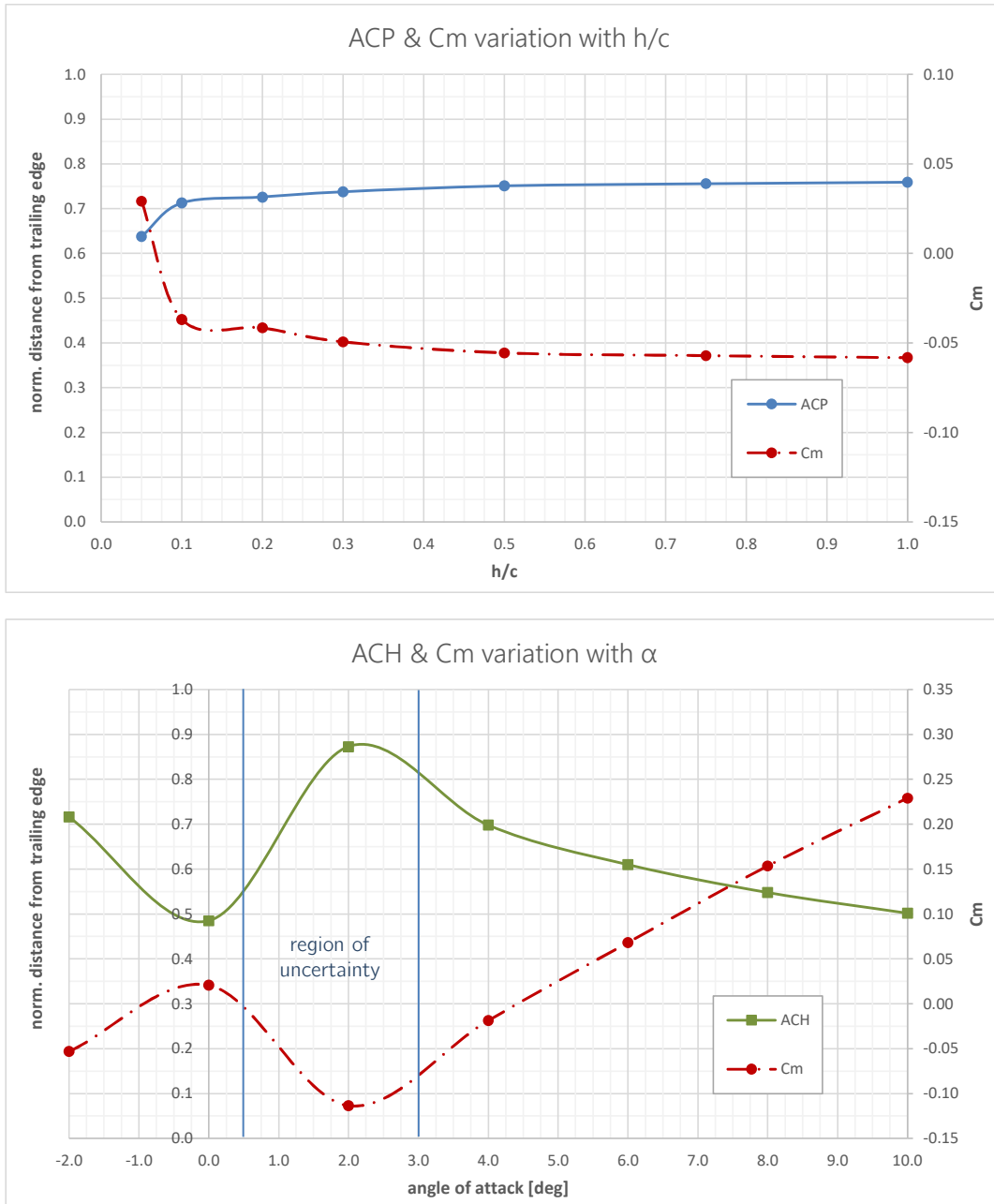


Figure 4-12 Positions of ACP (top) and ACH (bottom) for DHMTU 10-40.2-10.2-60.21.5

The results indicate that there is a narrow window where ACH is further forward than ACP. However, a significant portion of this range lies in the area marked as uncertain, with ACH forward of the quarter-chord position only between the angles $1.5^\circ \leq \alpha \leq 3.5^\circ$. Furthermore, it is exactly in this range that C_M is most negative. It is the opposite trend displayed by the NACA 25112, i.e. at these small angles the ACH position moved very far aft but was accompanied by a strong positive C_M . This is an area that needs further in-depth study before drawing definite conclusions about the relationship of ACH to ACP in this region.

Furthermore, Figure 4-9 shows that DHMTU lift-drag ratio is poor at $\alpha < 2^\circ$. The summary plot plus the detailed plots presented in Appendix 8.9 show a much more favourable drag bucket in the range $4^\circ \leq \alpha \leq 6^\circ$ at moderate heights.

It seems to be clear that the ACH moves rearward at larger angles, as was found with the NACA profiles. This trend appears consistent in each of the individual cases, as well as a general trend that covers all three profiles. In all cases, this movement is accompanied with a positively increasing moment.

Interestingly, it appears that although the DHMTU displays reasonably well-mannered characteristics through the GEZ, positive or nose-up moment is not achieved until EGE or $\alpha > 4^\circ$. Note that there is a small pocket of positive stability around $\alpha = 0^\circ$ but this quickly becomes negative as AoA is increased. This means that this section was not designed with self-stability as a priority and would require moderate control input to maintain longitudinal stability.

4.2.4 Movement of ACP & ACH

The three profiles share certain characteristics that should be considered fundamental behaviour. This includes a relatively steady position of ACP with respect to flying height, especially when out of EGE. Unfortunately, the position of ACH with respect to AoA is shown to steadily move rearwards as AoA increases.

Irrespective of whether unsteady flow simulation is required to accurately capture the precise flow-field around each profile in the questionable configurations, the confirmed trend indicates that both the ACP and ACH move significantly during operation in the GEZ. This movement does not lend itself well to establishing stick-fixed static stability.

The position of ACP appears to be more stable, remaining approximately in the OGE location until EGE region for the NACA 4412 and DHMTU profiles. The location was still relatively stable for NACA 25112 but there was more of a gentle transition between the OGE and EGE positions.

However, the same cannot be said for ACH. Both NACA 25112 and DHMTU displayed erratic ACH movements at small AoA, and could not be considered stable for NACA 4412 either. The quality of the data constituting these plots is of sufficiently high quality to rule out computational or procedural error.

There is no known study that has experimentally investigated this issue in depth and up to now the ACH concept has remained a mathematical curiosity. It cannot be stated with certainty that there is a neutral point with reference to height for airfoils operating IGE. The position of ACH seems to change for each AoA. This behaviour was exhibited by each of the three airfoils under analysis.

As the underlying concept of an aerodynamic centre is one to simplify design and analysis of airfoil performance, it is not clear how useful a constantly moving aerodynamic centre would prove to be in practice.

4.3 Wing Model Testing

Ideally, the wing profile would have extended fully to the sides of the towing tank. As for wind tunnel testing, this type of set up should result in 2D flow in the chordwise direction with minimal or no spanwise flow, as it would not be possible for tip vortices to be generated.

Due to the practicalities of the moving carriage, the towing rig apparatus and the glass sides of the towing tank, a safety margin was established that limited how close the wing and rig could be installed. The wing was constructed to allow a gap of approximately 125 mm to the tank sides (see Figure 4-13). The cross section of the support arms was circular on the upper parts to allow easier integration with the main transverse support member and simpler adjustment, and the lower parts were shaped flat bar sections. It was hoped the effect of these side supports would act similarly to wing tip fences to help keep the flow orientated in the chordwise or longitudinal direction.

When the measured C_L from experiment was compared to CFD, it became clear that there was a significant amount of spanwise flow. It was not possible to measure this flow directly, so it can only be deduced at this point by comparing theoretical 2D to the measured data. Aeronautical studies have shown how AR affects lift for various profiles, but there is no available data for the DHMTU section and the proximity to the bottom surface is also known to significantly influence apparent AR effects.



Figure 4-13 Position of wing near the bottom of the tank

As the intention was to have angle and height configurations numerically calculated and experimentally measured, these overlapped data points could be directly compared. Table 4-1 gives the lift coefficients from 2D CFD and 3D experiment for three angles and six height configurations, with the difference between each of them expressed as a ratio of 3D C_L over calculated 2D value.

Over these 18 points, the measured 3D C_L have a mean value of 82.4% of the calculated 2D, with one standard deviation within 9.4% of the mean. When the single highest and lowest outliers are excluded from the data set the mean remains similar at 82.3% and the standard deviation falls to 7.2%. For the purposes of this investigation, this gives confidence of accuracy of general trends and repeatability of these results.

Table 4-1 2D CFD lift coefficients compared to 3D experiment

h/c	0 deg			4 deg			8 deg		
	2D	Exp	Ratio	2D	Exp	Ratio	2D	Exp	Ratio
0.1	0.166	0.117	0.704	0.861	0.827	0.961	1.207	1.047	0.868
0.2	0.241	0.181	0.748	0.776	0.693	0.894	1.109	0.930	0.839
0.3	0.277	0.186	0.673	0.737	0.616	0.836	1.065	0.879	0.825
0.5	0.286	0.211	0.736	0.702	0.585	0.832	1.026	0.809	0.789
0.75	0.285	0.231	0.808	0.687	0.572	0.833	1.013	0.824	0.813
1.0	0.285	0.284	0.996	0.680	0.566	0.834	1.013	0.855	0.844
			0.778			0.865			0.830

When this mean value approach is applied as an efficiency factor across the 3D data set, a prediction or estimate can be made for the expected 3D results. This is shown in Figure 4-14 and Figure 4-15 for each of the tested angles, with the exclusion of -4° . This angle was not intended to be representative of a typical operating condition but was only included in the test programme as an extreme example at negative α .

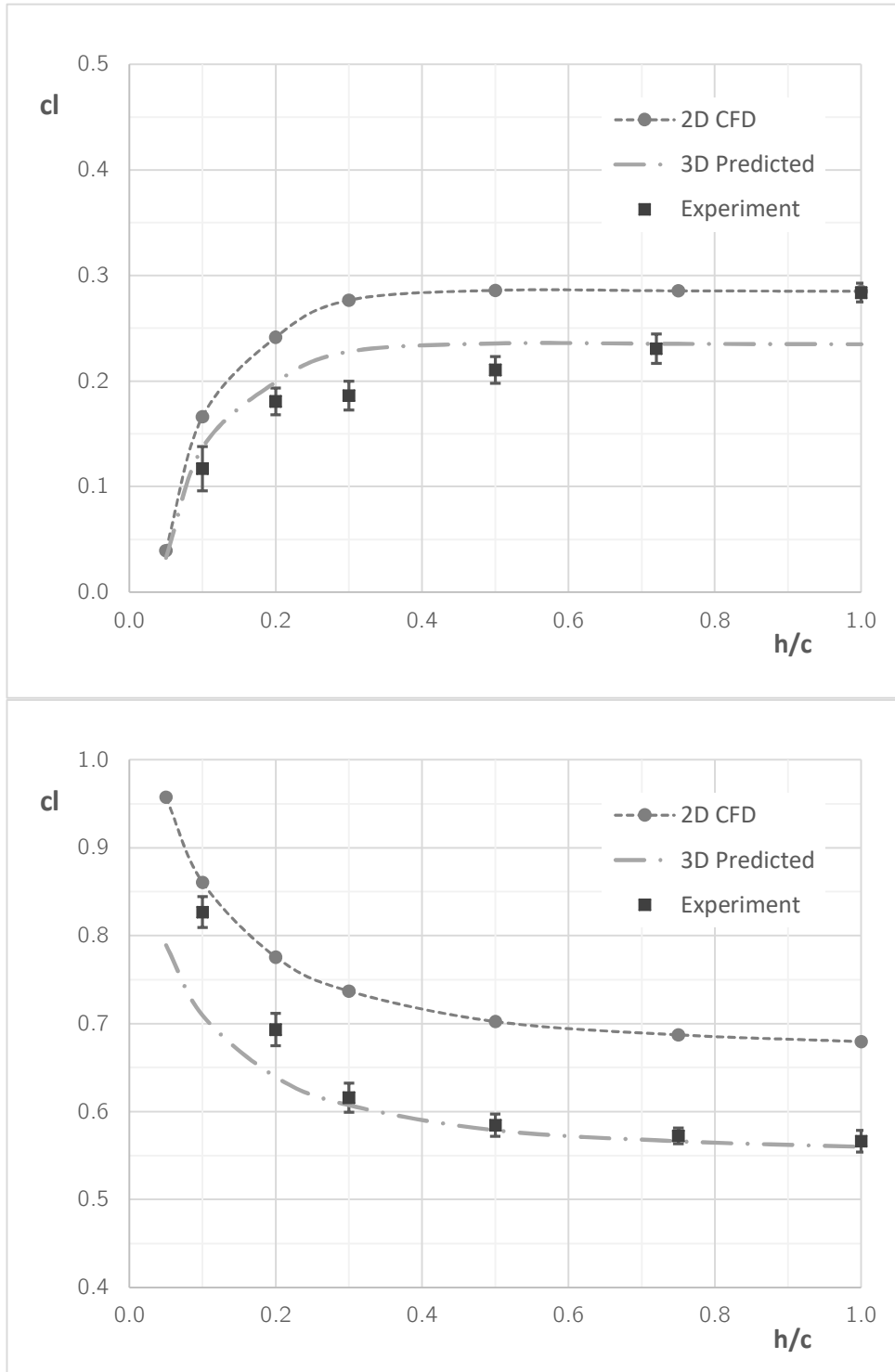


Figure 4-14 CFD prediction compared to experiment for 0° (top) and 4° (bottom)

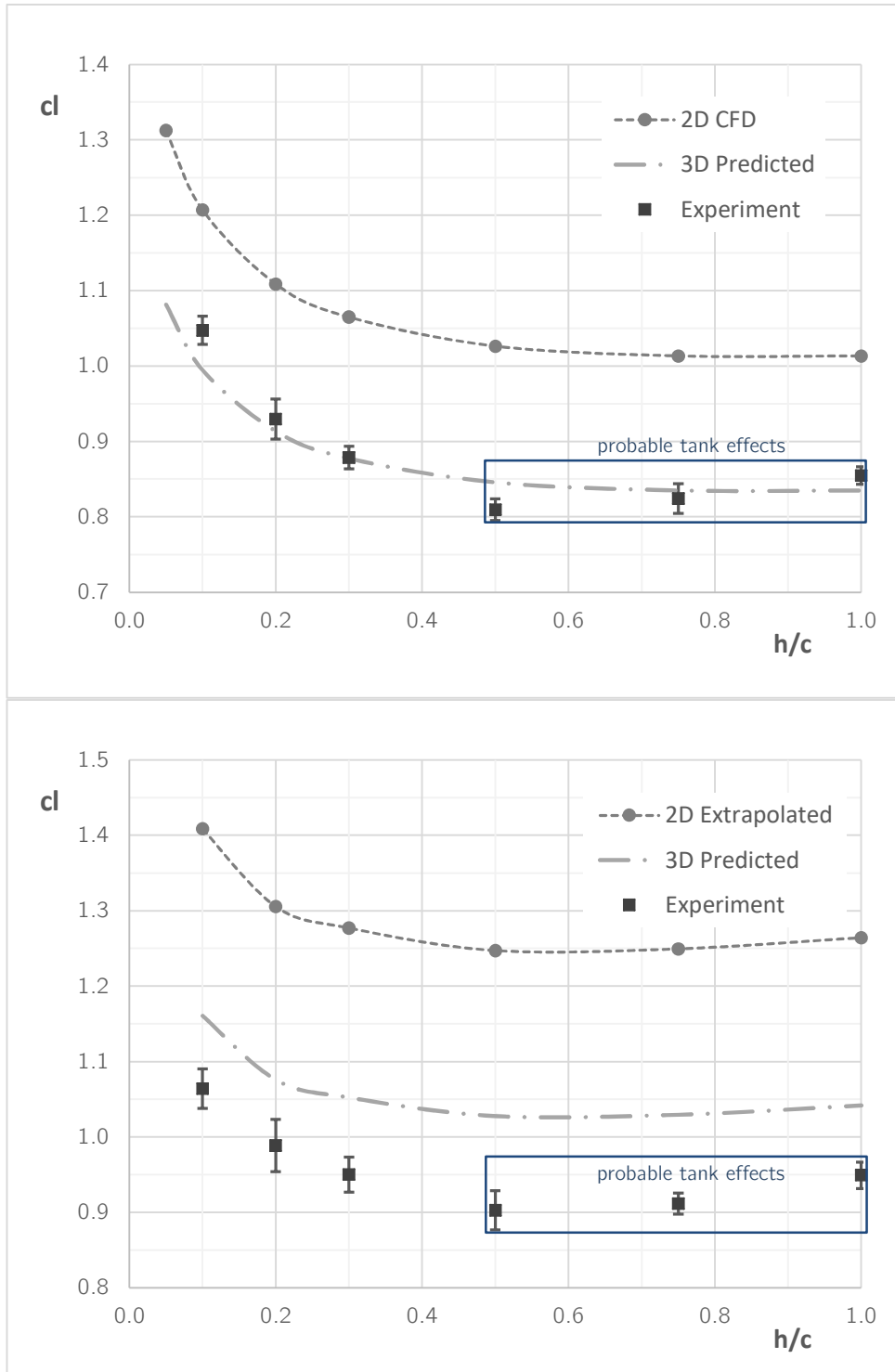


Figure 4-15 CFD prediction compared to experiment for 8° (top) and 12° (bottom)

Overall, the measured values generally agree with the prediction line, although at highest AoA the measured lift is considerably lower than expected. The measured lift was not much greater at $\alpha = 12^\circ$ than at $\alpha = 8^\circ$. There could be several reasons for this, most likely is that the water depth, i.e. distance above the airfoil upper surface to water surface, was not sufficient for this angle to develop the necessary bound vortex of fluid circulation.

It is known that hydrofoil lift breaks down as the foil approaches the water surface and would account for the greater lift expected at $\alpha = 12^\circ$ not becoming developed. As the net vorticity over the fluid domain must remain zero, there may therefore be an upper limit on the amount of lift a wing is able to produce in a tank of given dimensions. Figure 4-16 illustrates how the bound vortex interacts with the starting vortex and suggests that in a tank where water is the working fluid, water depth could limit the maximum size of the vortex formation.

The magnitude of the bound vortex then becomes the limiting factor. Best practice in numerical fluid dynamics indicates that the computational domain should extend 10 to 20 chord lengths from the airfoil surfaces in all directions to avoid boundary effects. Clearly that was not the case here and would require a water depth of at least 3.3 m for the given model size and height range tested.

In a related manner, all heights and measurements have been given normalised to chord length. This is entirely appropriate for 2D work but as noted previously, the flow in the tank was likely to have had a non-negligible spanwise component. As the span was more than four times greater than the chord, water depth above the wing upper surface was approximately only one span length. As shown in Figure 1-1, circulation effects including ground effects, are present in the spanwise direction as well as chordwise.

This leads to the conclusion that the water depth was not sufficient to accurately capture data for 3D wing across all angle, height and speed ranges. The intention of these tests was not to test a 3D wing per se, but the results suggest that although the test confirmed the magnitude of forces IGE in most of the configurations, the test set up was not sufficient to ensure 2D flow across the entire test range and in some cases resulted in interaction with the water surface or tank sides that affected the measured data.

In addition to the finite aspect ratio effects, the plots at $\alpha = 8^\circ$ and $\alpha = 12^\circ$ demonstrate a weakly U-shaped profile with lift actually decreasing slightly as the wing approached the bottom surface before increasing as expected. It is not known why this occurred, although the effects of water depth above the wing may again be the most likely explanation. This tendency was not observed in any of the numerical solutions and is not reported on in other published data. This has been marked on the plots in Figure 4-15 to indicate that this behaviour is highly unlikely to be a fundamental phenomenon and is instead an artifact of the test set up and facility.

Furthermore, not only was water depth a potential issue but there was no way to account for interaction between wingtip vortices (spanwise) and the bound vortex (chordwise) due to restriction of the tank sides. PIV techniques would have been helpful in determining flow patterns and interactions and were discussed for the testing programme but were not available at the time. The side supports connecting the towing rig to the wing possibly provided some amount wingtip fence effect but not enough to mitigate the spanwise flow in all cases.

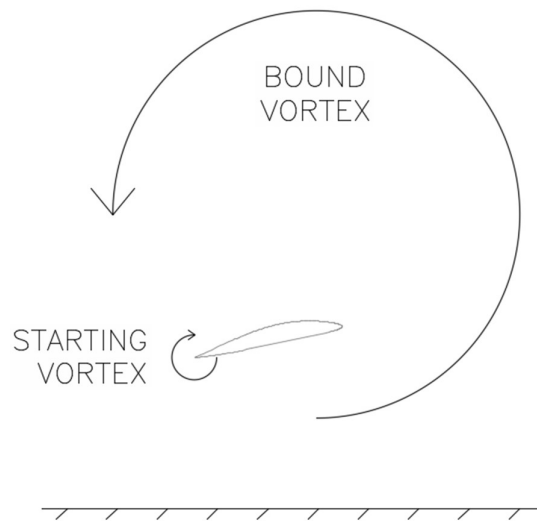


Figure 4-16 Diagram of circulation around airfoil showing starting & bound vortices

5 Wing-Hull Combined

In order to assess the combined influences of the hull and wing requirements, a parametric geometry model incorporating the principal dimensions and weight relationships was developed. Limited to consideration in the longitudinal direction, estimated mass properties, lengths and relative positions were used to assess feasible layouts.

Lengths and distances were nominally normalised to hull overall length, l_h , while masses and weight properties were given as a proportion of the total. Structural Weight Fraction (WF) estimates were assigned for the wing, hull and an allowance for propulsive machinery, along with their respective estimated centres.

The wing planform was assumed to be prismatic, *viz.* a rectangular wing without taper. Hull characteristics were as given in the previous sections.

The constraints imposed were:

- (I) the LCG of the combined wing and hull must coincide;
- (II) the relative positions of LCG, ACH and ACP must be as given in equation (1-6) and described in Section 1.3.1.2 to ensure longitudinal static stability;
- (III) structural WF of the wing was specified as an input variable, as a proportion of the total vessel weight, the machinery allowance was held constant at 10%, with the hull weight making up the remainder.
- (IV) a configuration could be considered stable once the overall LCG was forward of the overall AC.

The governing equations for the parametric model were based on mass groups and moments, assigned to primary components of wing, hull and machinery groups.

Input variables were wing weight as a proportion of the total, wing length as a proportion of the hull length and wing offset, indicating how far aft the TE overhung the transom as a proportion of the hull length.

Quasi-variables were used for components that could be readily varied but generally held constant throughout, such as estimated CG_{wing} as a proportion of its own chord length, estimated CG_{hull} as a proportion of its own length, and machinery mass and CG as a proportion of total mass and hull length, respectively.

Combined LCG was calculated by simply summing moments and masses such that:

$$d_{lcg} = \frac{m_w x_w + m_h x_h + m_m x_m}{m_w + m_h + m_m} \quad (5-1)$$

where variables m and x denote mass and position, respectively, and subscripts w , h and m denote wing, hull and machinery, respectively

Determining location of AC was done by calculating the local position with respect to its own chord and then offsetting forward or aft depending on wing offset input variable:

$$d_{acw} = ac_w l_w + d_{te} \quad (5-2)$$

where ac denotes aerodynamic centre, l_w denotes chord length of wing and d_{te} denotes offset from transom

Longitudinal stability was assumed once the position of overall LCG moved forward of AC_{wing} , in accordance with conventional static stability guidance.

5.1 Longitudinal Stability with Wing Alone

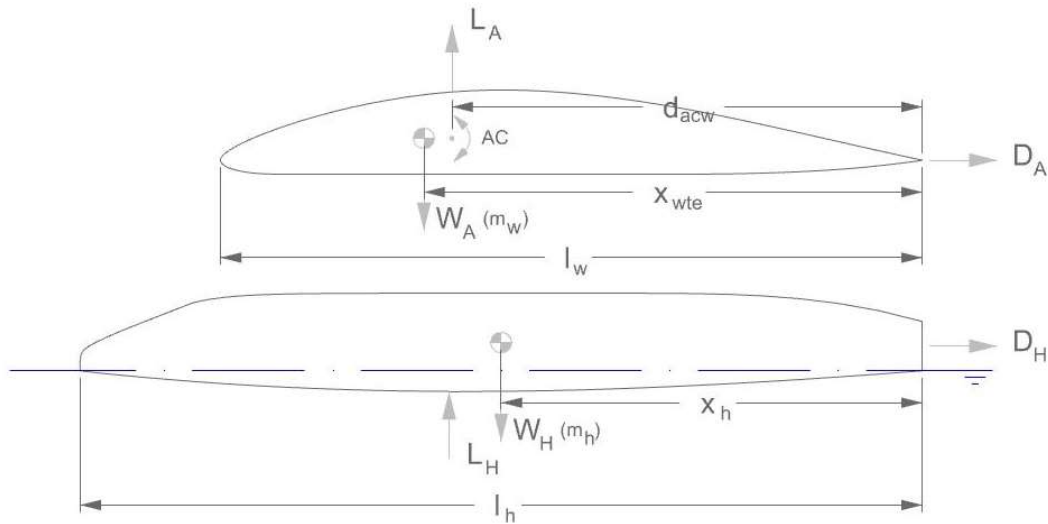


Figure 5-1 Graphical representation of main parameters used in geometry model

Ideally, the chord length of the wing would be as long as possible, as this results in a shorter required span for a given wing area, provides a greater internal volume for a given chord-thickness ratio (beneficial for BWB-type concepts), and results in a lower effective flying height with corresponding GE benefit for an absolute measured height.

As LCG of the hull was already determined by LCB position and the immersed cross-sections as given in Section 2.1, it is evident that the chord length of the wing cannot extend the full length of the hull ($l_w = 1.0 l_h$) when the wing TE is aligned with the hull transom, otherwise the vessel LCG position would be too far aft for the wing to achieve static stability. Therefore, the chord length should be shorter than the hull length in most cases and may additionally be offset aft, so that the TE ends up behind the transom. The amount of aft offset is dependent not only on the chord length of the wing, but also on WF_{wing} , so that as the wing represents more of the total weight its location must necessarily move aft to maintain alignment of weight centres. The effect of the relationship between MAC and overall LCG is represented graphically in Figure 1-15.

A chart showing the primary relationships for a preliminary configuration is presented in Figure 5-2 for four wing weight fractions, from 30% to 60% of the total vessel weight. It can be seen that in order to achieve minimal stability for a given chord length, e.g. 80% of the hull length, the wing TE must be located at least 10% of the hull length aft of the transom, when the wing accounts for 30% of the all-up weight. However, if the wing were heavier due to construction techniques or materials and accounted for 60% of the total weight, the TE must be located at least 23% of the hull length aft of the transom.

As compactness of structure was one of the project objectives, an excessive overhang of unsupported wing structure would not be ideal. Therefore, minimising wing box and skin structural weight directly results in a lighter vehicle but also allows for a more compact configuration.

As payload was not explicitly included as a separate weight group, the estimated mass should be rolled into WF_{wing} , as it is likely to correspond closely with LCG_{wing} at approximately $0.35 l_w$ from LE, in the range of maximum profile thickness. This would be considered an acceptable estimate for low-density payloads at early-stage design.

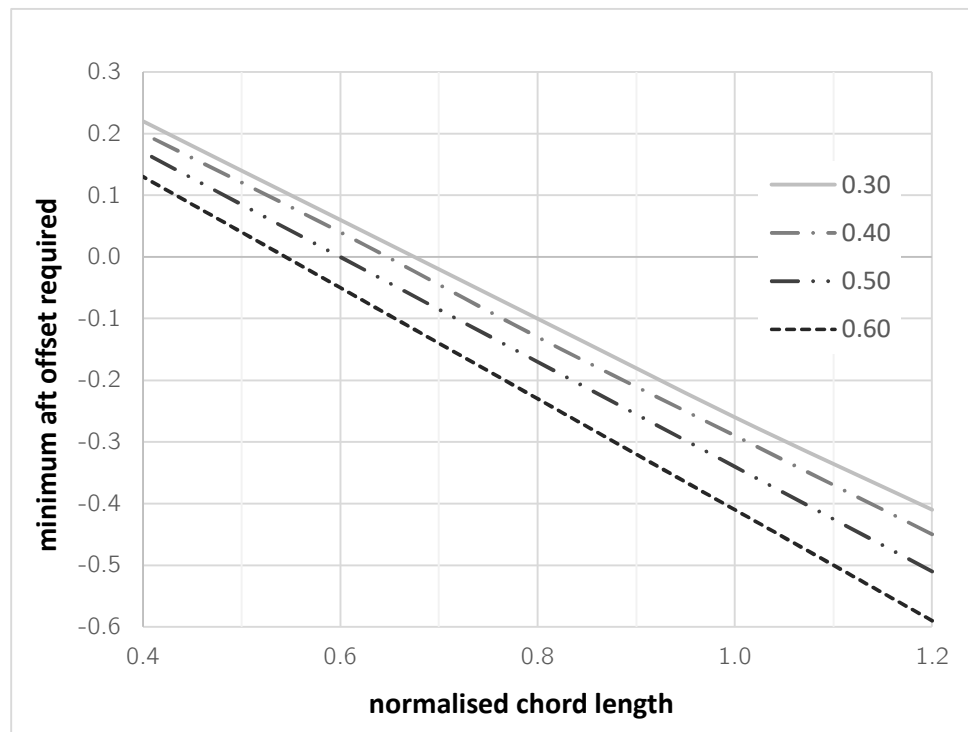


Figure 5-2 Minimum aft offset required for various chord lengths at 4 weight fractions

Table 5-1 shows the dimensions for a sample wing layout that satisfies the static stability requirements, where the wing chord length is 75% of the hull length, $WF_{wing} = 0.40$, aft overhang of the TE is 15% so that the LE is correspondingly 60% of the hull length forward of the transom, resulting in unsupported hulls (i.e. without crossdeck structure) for the forward 40% of the vessel length.

Table 5-1 Sample configuration of suitable geometry

item	symbol	value	comment
wing weight of total	m_w	0.400	estimated wing mass
wing length of total	l_w	0.750	wing mean chord
wing te dist from transom	d_{te}	-0.150	positive=fwd, negative=aft
wing lcg from te	x_{wte}	0.650	estimated wing cg
hull lcg from transom	x_h	0.600	estimated hull cg
mach'y lcg from transom	x_m	0.200	estimated machinery cg
mach'y weight of total	m_m	0.100	estimated machinery mass
hull weight of total	m_h	0.500	mass of hull only
hull length of total	l_h	1.000	vessel loa
wing lcg from transom	x_w	0.338	distance from transom
wing le from transom	d_{le}	0.600	distance from transom
wing+hulls lcg from transom	x_{w+h}	0.468	distance from transom
wing ac from transom	d_{acw}	0.413	assumed 0.25 chord
wing+hulls dist ac aft of lcg	$ssm1'_{w+h}$	0.056	OK
wing+hulls ssm by chord	$ssm1_{w+h}$	0.074	as percentage of chord length
combined lcg from transom	x	0.455	vessel lcg
combined dist ac aft of lcg	$ssm1'$	0.043	OK
combined ssm by chord	$ssm1$	0.057	static margin as chord length

5.2 Static Stability Margin with Wing + Tail

The primary aim of the preceding section was to quickly determine potentially stable configurations where the entirety of the required lift was generated by the main wing, with the tacit implication that control during manoeuvres, take-off and landings, etc., could be effected by small modifications to the wing surface in the normal way.

Currently, all WIG craft from past and present have utilised significant control surfaces, typically in the form of a conventional aft tail. In contrast to GA aircraft, these tails are also typically lifting surfaces instead of conventional tails generating down-force. One of the main benefits is that these can provide some of the required lift and has the effect moving the combined AC aft. As such, configurations that may have been shown to be unsuitable in the previous section, may be viable with the inclusion of a lifting tail surface.

Furthermore, configurations that may achieve a minimally-acceptable static stability can be made more robust by the addition of a small tail. Note that although this assessment has been based on an aft tail arrangement, as the control input acts as a moment on the rigid body, a forward mounted canard may serve the same purpose if located sufficiently far forward to generate the required moment.

During early WIG development, Irodov (1974) showed that although meeting the static stability criterion should indicate satisfactory stable flight, a Static Stability Margin (SSM) of approximately $0.1c$ was necessary to ensure stability during non-equilibrium events, e.g. manoeuvring, etc. Interestingly, increasing SSM much above this value can cause the craft to become overly-stable and subject to periodic oscillations. Therefore, a target value of $SSM = 0.1c$ was applied to determine required tail force.

Required tail lift as a proportion of total lift was calculated by determining the difference between the actual and desired margins and applying at the distance of AC_{tail} from AC_{wing} :

$$L_t = \frac{(ssm_d - ssm_a) l_w}{d_{acw} + d_{act}} \quad (5-3)$$

where ssm denotes static stability margin, subscripts d and a denote desired and actual, respectively, l_w and d_{acw} as before

Longitudinal position of AC_{tail} has been held constant at $0.05 l_h$ across all cases, as a representative location near the aft extremity of the hull. Tail moment is calculated prior to determining force required, so it is straightforward to modify this location to determine control force required at a different point, if desired.

The LCG position for the hull has also been held constant, such that there is no dependency of WF_{hull} as WF_{wing} varies. Although no weight category for payload was included, this can be acceptably estimated as being part of WF_{wing} . No allowance has been made for the additional structural weight of the tail.

Figures Figure 5-3 and Figure 5-4 show the lift required from tail control surfaces, as a proportion of total lift. The plots cover the extremities of the practical range $0.6l_h < l_w < 1.2l_h$ and are shown for five positions of aft offset of main wing, from 0 (aligned with transom) to 0.4 (TE overhanging transom by 40% of hull length).

The minimum value of $l_w = 0.6l_h$ was determined to be sufficiently short, as this tool is intended for craft of the long-chord type, as airplane-type configurations typically use much larger tail surfaces as an integrated part of their design. The upper bound of $l_w = 1.2l_h$ is likely to be overly long for any practical purposes but remains illustrative of the general trends.

The overall conclusions are that as the wing and/or payload gets heavier, i.e. represents a larger portion of the total mass, the amount of tail lift required to move the AC into an acceptable range increases. This is generally due to the wing being located to the rearwards of the vessel, in order to get AC_{wing} into a suitable location. Therefore, an increase in wing weight generally results in an overall shift of LCG aft, which in itself requires an even further movement of AC aft. When the wing alone cannot achieve this, tail force input is a necessity.

From a different perspective, when chord length and wing weight are held constant, as the wing is positioned further aft the tail lift required decreases, as the wing placement shifts the vessel LCG aft.

With the main wing positioned right aft, more tail force is required as wing weight rises. This is due to the greater proportion of overall mass causing a rearwards movement of LCG while the main aerodynamic surface remains stationary, necessitating greater tail input to compensate. This is clearly seen in the plots of the -0.4 line as greater tail forces are required across more chord lengths as WF_{wing} increases.

An interesting effect occurs when there is no aft offset, configurations at $l_w < 0.9$ behave as all others, but when $l_w > 0.9$ tail force requirements actually decrease. This is due to the geometric position of LCG_{wing} being forward of LCG_{hull} in this arrangement, so that as WF_{wing} increases, under the assumption of its weight acting at LCG_{wing} , the overall vessel LCG actually moves forward. This effect is seen to some degree in the other offset lines also, being just visible in the upper end of the -0.1 line, and especially at $WF = 0.60$, where there is something of a convergence upon tail force of 40% once chord length reaches $1.1l_h$ for all placement options.

As the point of application of tail force did not vary with wing chord length but was instead held to a constant location, the figures show larger forces to generate the restoring moment than would be expected if the tail structure were allowed to shift aft as l_w or aft offset increases. However, this shift would also cause a weight shift aft, which would then cause an increase in the required tail force to maintain SSM. At this stage of development and analysis, the constant tail position was determined to be a suitable compromise.

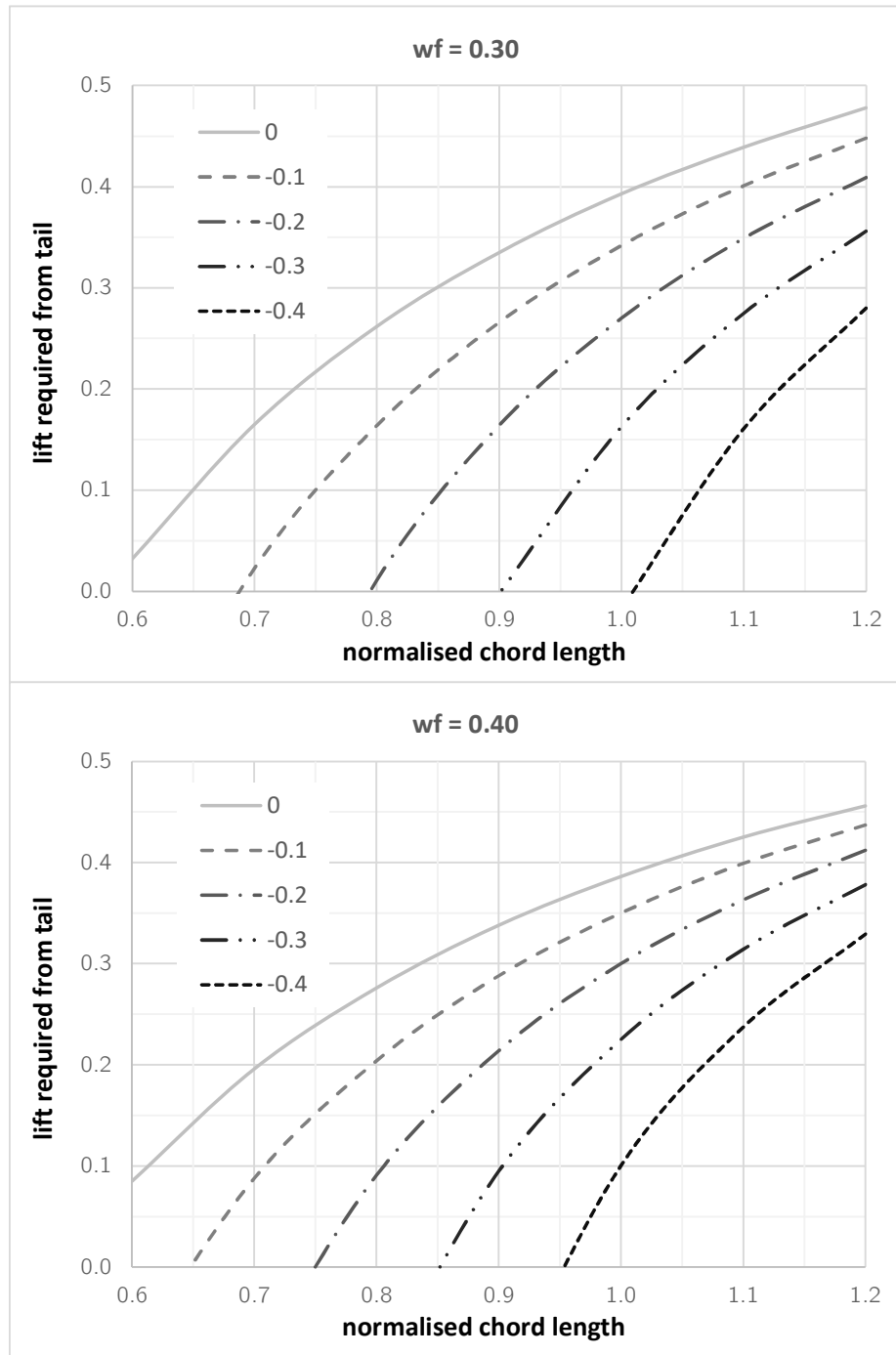


Figure 5-3 Tail lift required for target SSM, WF=0.30 & WF=0.40

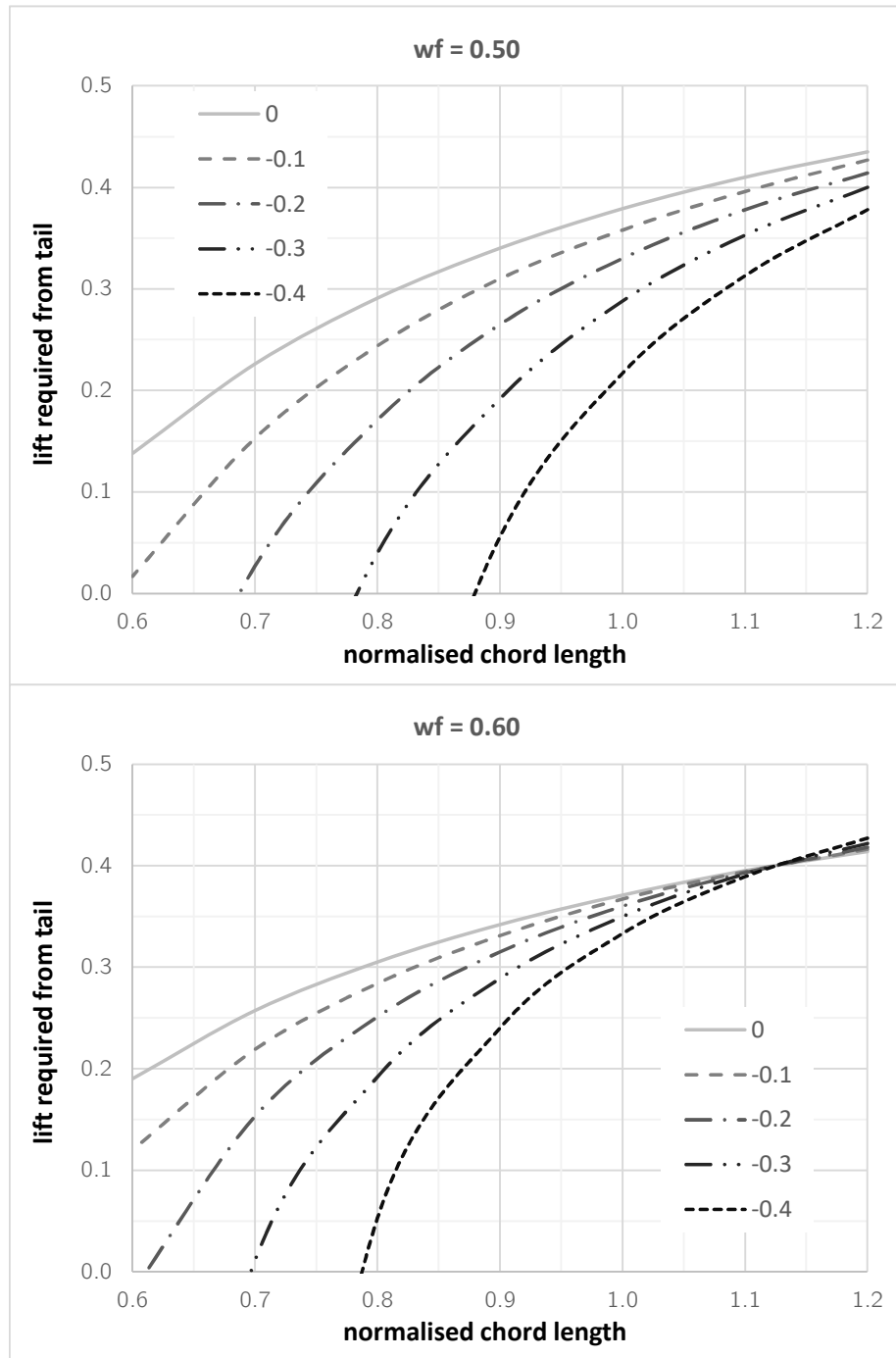


Figure 5-4 Tail lift required for target SSM, WF=0.50 & WF=0.60

5.3 Lift and Drag at Take-Off

Once some preliminary dimensional parameters have been decided, calculation of forces and power required for take-off can be approached, along with relationships between take-off and cruise velocities.

As described in Section 2.1.3, a first approximation of vessel size was determined to be around 20 m LOA. Therefore, when $l_h = 20$ m with $l_w = 0.75 l_h$, as shown in Table 5-1, the resulting wing chord length $l_w = 15$ m. Assuming a square planform, $AR = 1$, the wingspan becomes 15 m with zero taper or sweep.

The vertical position of wing TE was assumed to be 0.75 m above the static waterline, corresponding to a flying height of $\bar{h} = 0.05$. The hulls extend below this point to provide the required buoyancy for flotation.

Using the aerodynamic coefficients from the DHMTU 10-40.2-10.2-60.21.5 profile derived in the previous sections, a lift coefficient of $c_l = 1.172$ is achieved at this height at $\alpha = 6^\circ$. Assuming a target take-off velocity of $V_{TO} = 50$ kt, the wing generates a lifting force of approximately 107 kN, equating to a maximum take-off weight $MTOW = 10\,900$ kg. Sensitivity of MTOW to selected AR is shown in Figure 5-5. Moderate values for V_{TO} and MTOW were selected, which also appeared feasible when taking practical considerations into account, such as structural requirements for satisfactory robustness, powering options to enable to vessel to reach required speeds, etc.

Profile drag at this condition was shown to be $c_d = 0.0146$ for a clean 2D wing, which must be augmented by 3D form effects. Estimating this in the GE condition is not straightforward, so a general approximation incorporating AR effects and span efficiency factor has been used. This is likely to overestimate C_{Di} so should be considered an overly conservative approximation.

An allowance for skin friction drag was also included to arrive at a total aerodynamic drag at take-off, $D_{ATotTO} = 66.4$ kN. Of course, as this corresponds only to the aerodynamic surfaces, hydrodynamic drag must also be accounted for. Summary values of aerodynamic characteristics are presented in Table 5-2.

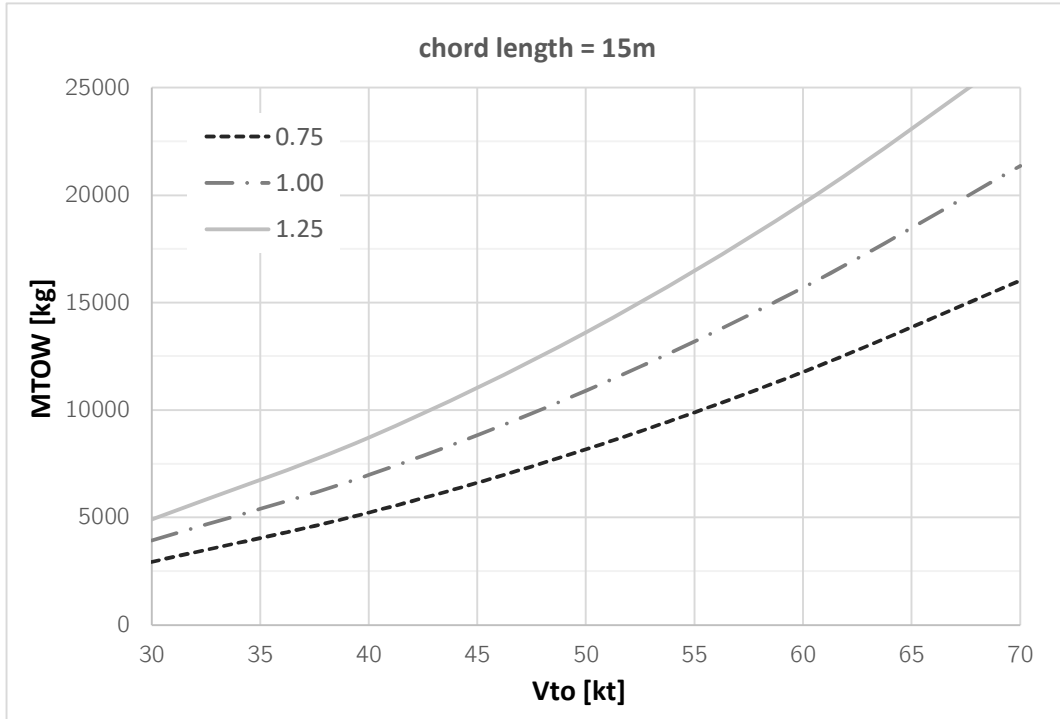


Figure 5-5 Maximum take-off weight as a function of take-off velocity for chord length = 15m at three aspect ratios

The wing calculations have assumed $V_{TO} = 50$ kt, by definition requiring the hulls to be lifted free of the water surface at this point. The resistance curves shown in Sections 3.1 and 4.1 were generated from a series of fixed-body tests at varying angles of trim and still-water static displacements, i.e. the immersed volumes displaced at rest represented a given proportion of the designated full-load displacement. During the aerodynamic alleviation process, the effective displacement of the full-size vessel reduces due to the aerodynamically generated lift offsetting the vessel weight. In order for any WIG to generate sufficient lift to take-off at a given velocity, it must also be generating lift at velocities less than V_{TO} , in accordance with the instantaneous velocity and lift coefficient for wing configuration, viz. angle of attack, flap deployment, etc. The model test results at less-than-full displacement can now be used to determine hydrodynamic resistance during this transitional take-off phase.

Table 5-2 Aerodynamic characteristics for sample wing with Vto = 50kt

item	symbol	unit	value
chord, root	c_r	m	15.000
span	b	m	15.000
taper ratio	λ	-	1.00
sweep, leading edge	Λ_{le}	deg	0.00
chord, tip	c_t	m	15.000
tip le back from root le	d_{le}	m	0.000
sweep, quarter chord	Λ_{qc}	deg	0.00
planform area	S_{ref}	m ²	225.00
aspect ratio, average	AR	-	1.000
span efficiency factor	e	-	0.618
coefficient of lift, takeoff	CL_{to}	-	1.172
takeoff velocity	V_{to}	kt	50.00
coefficient of lift, cruise	CL_{cr}	-	0.277
fluid density	ρ	kg/m ³	1.225
kinematic viscosity	ν	m ² /s	1.80E-05
reynolds number, takeoff	Re_{to}	-	2.14E+07
lift produced	L_{to}	N	106846
lift produced	L_{mtow}	kgf	10896
cruise velocity	V_{cr}	kt	102.8
cruise to takeoff ratio, speed	$V_{cr}:V_{to}$	-	2.06
assumed form drag, takeoff	Cd_{oto}	-	0.015
assumed form drag, cruise	Cd_{ocr}	-	0.011
coeff of induced drag, takeoff	Cd_{ito}	-	0.707
coeff of induced drag, cruise	Cd_{ito}	-	0.040
coefficient of friction	Cf	-	0.003
friction drag, takeoff	D_{fto}	N	498
form drag, takeoff	D_{fto}	N	1367
induced drag, takeoff	D_{ito}	N	64495
total aero drag, takeoff	D_{atotto}	kN	66.36
friction drag, cruise	D_{fcr}	N	2108
form drag, cruise	D_{fcr}	N	1003
induced drag, cruise	D_{icr}	N	15243
total aero drag, cruise	D_{atotcr}	kN	18.35
cruise to takeoff ratio, drag	$D_{cr}:D_{to}$	-	0.28

The upper bound for total vessel displacement is MTOW, due to aerodynamic considerations. This value can then be used as the maximum displacement design limit. As stated in the previous section, a nominal hull length of 20 m results in a model scale factor $\lambda = 6.67$. Although not an integer value as seen in Figure 2-3, this has negligible impact in the data processing due to the non-dimensionalised speed and resistance results.

In typical salt water conditions, a mass of 10 900 kg requires an immersed volume of 10.6 m³ for buoyant equilibrium. At the selected $\lambda = 6.67$, a geometrically similar hullform would displace 8.7 m³ on an even keel draught of 0.500 m. Therefore, only a single hull would be required to support the total mass but the vessel could be configured with outriggers, or amas, either side to ensure adequate transverse stability, to provide an additional 0.95 m³ of buoyant volume per side and to act as an endplate to contain the over-pressure on the lower surface of the airfoil.

If the wing generates full lift at velocity of 50 kt, the same wing in the same configuration generates half of this lift at a velocity approximately 35.4 kt. This means that as the vessel accelerates, resistance increases as with any vehicle but this resistance does not increase at the same rate as conventional marine vehicles, due to the effective weight being offset by the aerodynamic alleviation. For example, at model speed 7 m/s, resistance at full displacement is 53% greater than at 50% displacement (see Appendix 8.4), with a linear increase in power required to achieve that speed. Instead of this power being absorbed to overcome drag, the WIG simply begins to lift and continue acceleration.

The geometry model was extended to include calculation of airfoil lift and drag based on the aerodynamic coefficients derived by CFD including the effect of parasitic drag on all of the vessel wetted surfaces, and hydrodynamic drag scaled from the model test results. As the nature of experimental results are discrete data points, interpolation was used to estimate unknown values. For example, model test results were available for the full displacement condition, also for 80%, 50% and 25%, whereas the aerodynamic lift is generated on a continuum from zero at zero speed to maximum at take-off. Hydrodynamic drag components included the scaled results from 0° and 3° trim tests, which were then augmented by approximately 50% to account for the drag of the two shorter side hulls. No allowance was made for submerged appendages or running gear as the vehicle would be intended to have airborne propulsion.

Figure 5-6 shows the aerodynamic and hydrodynamic components for the vessel parameters described. For some WIG types such as PAR and aircraft-type configurations, hydrodynamic forces have represented a larger proportion of the total until take-off. Aerodynamic form drag has been estimated conservatively and may account for more of this estimate than would actually be the case. However, a long-chord type WIG such as this would be expected to have greater surface areas with corresponding higher parasitic drag.

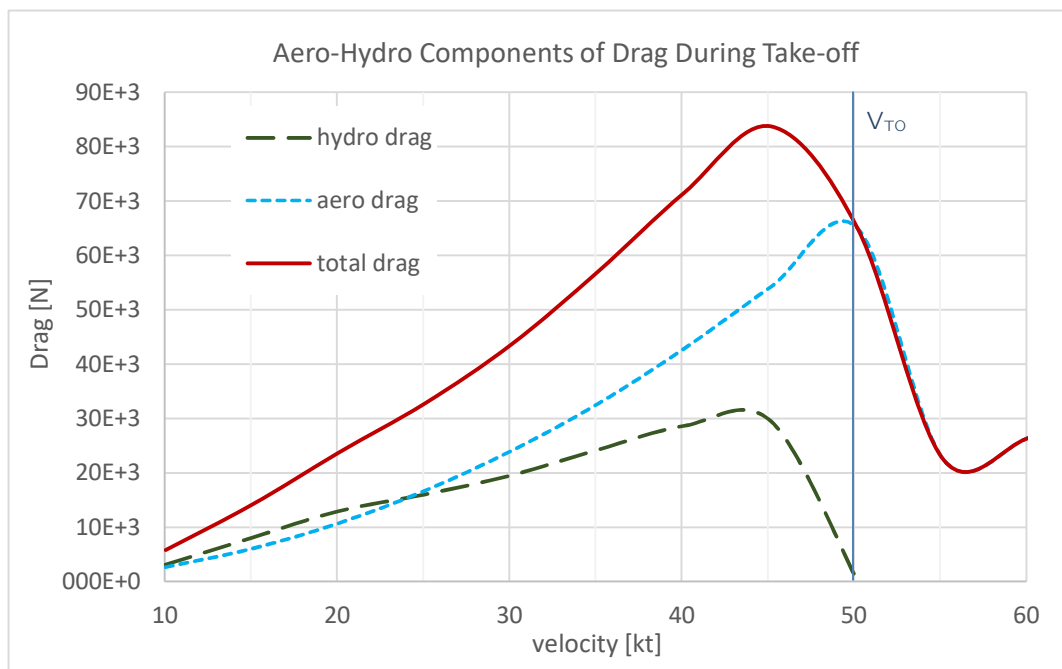


Figure 5-6 Aerodynamic & hydrodynamic components of drag during take-off for $V_{to} = 50\text{kt}$

Table 5-3 Summary of principal parameters for a sample WIG conceptual design

VEHICLE: INERTIAL			
Mass	10.90	t	Total mass
LCG	9.10	m	Longitudinal position of CG (from transom)
VCG	1.75	m	Vertical position of CG (from keel)
VEHICLE: GEOMETRY			
LOA	23.25	m	Total length of the vehicle
Beam	15.50	m	Total width of the vehicle
Draft	0.50	m	Draft
HULL/S			
Number (main)	1	-	Number of main hulls
Length (main)	20.00	m	Main hull LOA
Beam (main)	1.67	m	Hull beam (single)
Number (side)	2	-	Number of side hulls
Length (side)	15.00	m	Main hull LOA
Half-beam demihull	7.50	m	Demi-hull spacing (cl-cl)
WING/S			
Wing length	15.000	m	Wing chord length (MAC)
Wing span	15.000	m	Wing span
Wing profile		-	DHMTU
Wing planform		-	Rectangular
LAC	13.46	m	Longitudinal position of AC from transom
VAC	3.15	m	Vertical position of AC from keel
ETA	3	deg	Angle between keel and mac
POWER AND PROPULSION			
Propulsion type	Aero Turboprop	-	Type of propulsion
Total power req'd	2370	kW	Total power installed
Cruise:takeoff power	0.62	-	Ratio of cruise power to takeoff power
Number of engines	2	-	Number of engines

The geometry tool was then expanded to calculate powering requirements for the take-off phase and steady-state cruise. An assumed propulsion coefficient $\eta_P = 0.80$ for turboprop engines at low Mach number was assigned, which combined with several other losses to produce an overall propulsive coefficient of $\eta_{OPC} = 0.72$. This value was used for both take-off and cruise phases although is easily modified if a more accurate estimate is found.

Installed shaft horsepower $P_S = 2370$ kW is required to meet the drag requirements during take-off. The DHMTU profile in a rectangular planform was selected, with aerodynamic coefficients from the $\alpha = 6^\circ$ condition. The angle of incidence between MAC and datum was fixed at $+3^\circ$, resulting in the tested hull data for 3° trim being used for model inputs during the take-off phase. Cruise coefficients were taken from the $\alpha = 2^\circ$ condition. Previous analysis has indicated that this is not the most efficient AoA for L/D efficiency (see Section 4.2.2), however ideal ACP and ACH locations at this angle have a beneficial stabilising effect.

In any case, power required for take-off is greater than cruise power in equilibrium flight. Cruise power is calculated as $P_{CR} = 1350$ kW once hydrodynamic forces are removed and a steady-state height $\bar{h} = 0.1$ is assumed with resulting $V_{CR} = 102$ kt. Reserve power is beneficial for manoeuvring during disturbances or general navigation, or for flying at greater heights where aerodynamic efficiencies decrease.

Future iterations of the geometry model can include planform effects, such as taper and sweep angle, to investigate how the position of critical parameters, e.g. LCG, ACP, ACH, etc., can be modified by changes to the 3D configuration.

Finally, the assessment criteria to determine whether the overall configuration of this sample WIG concept has achieved its intended design space was specified in the introductory chapter; the benefit of GE transportation lies predominantly in improved transport efficiency.

The concept of transport efficiency was presented in Section 1.1.3, as a quantitative methodology to compare the efficiency of radically different modes of transportation. Specific tractive force, ε , was defined as a function of vehicle weight, speed and motive power required.

For this initial conceptual design, the target was to end up in the central region shaded yellow, above the Gabrielli-Karman line, as this represents a gap in the design space that might be filled by this particular type of vehicle.

Table 5-4 lists the parameters required to access the graph, specifically for $\varepsilon = 0.063$ at $V_{CR} = 190.5$ km/h. It is evident that the conceptual WIG does indeed lie within the intended design space, albeit toward the top of the region. The implication is that as technological advancements occur, vehicle geometries become further refined and more efficient. As the field of GE research and development progresses, the power required to move a given mass at a given speed would be expected to continue to decrease.

Table 5-4 Parameters for calculating transport efficiency

item	symbol	unit	value
total weight	mg	kN	106.8
cruise velocity	V_{cr}	m/s	52.9
cruise velocity	V_{cr}	km/h	190.5
cruise power	P_{cr}	kW	1350
specific tractive force	ε	-	0.063

6 Summary & Conclusions

This project focused on developing the required knowledge and engineering data to be used in the first-principles conceptual design of a WIG vehicle.

The work described in the previous sections has shown how a model was designed and built to a novel hull shape that was experimentally tested at very high speed to assess its potential performance in the take-off phase of WIG operation. A separate process has been documented, that shows how to obtain reliable numerically-derived 2D aerodynamic coefficients for various wing profiles across a range of angles and heights IGE. Finally, another experimental programme was conducted and presented here, for a wing model with unusual profile that was towed near the bottom of a water tank to replicate the physics and flow patterns of a wing immersed in an incompressible fluid moving over static ground in order to confirm and validate the numerical data.

The three work programmes were carried out concurrently.

Using the data derived from the experimental testing and numerical analysis, design relationships were established showing the range of suitable wing lengths and positions to ensure static stability, including detailing the effect of the wing and payload weight group on allowable length and position, and showing how the inclusion of a tail control surface can allow a wider range of configurations, along with the tail force required in each case. Finally, a demonstration of predicted drag performance for a sample case study of a WIG with specific parameters during the take-off phase was presented, along with the principal particulars of a WIG developed using this method that was compared to the original design brief.

6.1 Summaries

6.1.1 Summary of Hull Model Programme

Initially, a set of criteria were developed to direct the design of an untested hullform. A CAD model was created that incorporated the criteria and a physical plug was milled from high-density foam. A fibreglass skin was vacuum-bagged over the plug, after securing fittings for towing rig attachment points.

A custom towing rig assembly was designed to fit the carriage in the test facility, that would allow the model to be positioned securely and accurately. The test plan was created to cover the main areas of interest in the limited time that was available. Several days of testing were carried out, with suitable model instrumentation and data acquisition systems.

The test results were analysed that showed good performance at the extreme speeds that were the key area of interest. The data covered one non-zero angle of incidence, as the original plan was to have further tank testing time at a future date.

Unfortunately, this did not occur so the completion level of the test matrix was less than ideal. However, the data that was recorded showed some interesting features regarding force magnitude and comparison between different trim angles. Video capture of many of the runs was helpful in qualitative assessment of flow patterns and possible reasons for certain results.

As this testing programme was by no means exhaustive, there is plenty of further work that could be carried out by reusing the assets that were created and building upon the knowledge base.

6.1.2 Summary of Aerodynamic Data Programme

This part of the project was necessary to establish a reliable and comprehensive database of aerodynamic coefficients for wings operating IGE. This would lay the foundation for future work carrying out the design and analysis of WIG vehicle performance.

After preliminary assessment of the tools available for this task, a RANS CFD code was selected. There were not many resources to consult, so a period of trial and error ensued before gaining enough experience to understand how the computational processes should be set up to extract reliable and repeatable results for various profile types.

A scripted routine written for front-end ICEM to import profile geometry and computational domain specifically for GE applications. Validation of results was also complicated by the sparsity of accurate reference material.

Results were collated and analysed to populate the database and gain insight into behaviours and trends of the profiles IGE. A technique was developed to extract information regarding aerodynamic centres in pitch and height, as there was no practical information about these concepts in the public domain.

Where data appeared anomalous, further investigation was carried out to ensure there were no known input or computational errors. Even so, certain outcomes appeared to be sufficiently unusual to come to the conclusion that other physical effects may be occurring in some cases.

6.1.3 Summary of Wing Model Programme

In order to conclusively validate the computational results, it was decided to build a physical model for experiment. As there are numerous inconsistent and uncharacteristic results of GE testing in wind tunnels published, it was decided to use an unconventional but physically representative medium.

The university facilities had a low-speed towing tank available so the feasibility of using it for this application was scrutinised and found to be acceptable. A wing profile was then decided upon, and construction drawings created for the model and towing rig.

Fabrication was carried out in the local machine shop and when all build issues were resolved the apparatus was fitted to the tank. A test matrix was decided and testing proceeded.

After set up and calibration, the wing was lowered toward the bottom of the tank and the instrumentation recorded significantly higher vertical forces. Although not all results followed trends as closely as anticipated, this is often the nature of physical experiment.

Data was being collected and quickly plotted to minimise the chance of significant error in the results. As testing occurred over many days and having to occasionally remove and reposition the test rig, it is possible that measurement error crept in. It is also probable that certain tank effects affected the results, but the bulk of the data lines up well with computational prediction.

6.2 Conclusions

The overall aim of this project was to develop the requisite fundamental knowledge and engineering data in order to create a first-principles-based methodology for generating and analysing preliminary designs of a Wing-in-Ground Effect vehicle. As this is not a well-documented field, similar resources are presently not available. Accordingly, to assess the overall project effectiveness in context, reference must be made to the challenges documented in the literature review summary, given in Sections 1.4.1 and 1.4.2, to better understand the rationale for the programme of work undertaken.

The overall project aim was broken down into a number of broad areas of research and individual technical challenges that were determined to be of highest priority for investigation, which were then translated into objectives to be accomplished. Interdependent work packages were devised to address each of these objectives. Successful completion of the work packages would indicate achievement of the objectives. The final package consisted of the development a parameter-based geometry model that incorporated the research data combined with systematic relationships and input variables, resulting in a viable WIG configuration for conceptual design.

The technical merits of each objective-based work package are concluded in the following section. Each objective has been assessed for satisfactory completion, i.e. whether the target set out at project initiation has been fulfilled. Each package achieved its goal.

Therefore, the project aim is considered successfully completed.

Specific contributions to the scientific and engineering field of knowledge pertaining to GE theory and design have been categorised by design methodologies, new data and data validation methods.

6.2.1 Objective-Based Conclusions

The project objectives were derived to serve the overall project aims in a methodical and functional manner. Work packages were developed to achieve these objectives. These objectives are described in Section 1.4.3.

- a. **The first objective was to design, build and test a hull model with preferential characteristics for WIG use.** Ideally the hullform was to be suitable for waterborne operation at low- and moderate-speeds, leading to the possibility for a dual-purpose vehicle comfortable in air or water. Much of the usefulness of this work would come from the experimental test results, requiring a comprehensive test matrix. This matrix was not able to be completed in entirety. Fortunately, useful data was collected from the initial round of testing, which covered the high-priority configurations. Furthermore, as the hullform was based on slender hull concepts that are currently used on HPMV, performance and comfort in the lower speed regimes should prove satisfactory in an appropriate configuration.
- b. **The second objective was the creation of a comprehensive database of aerodynamic coefficients for profiles suitable for use IGE.** A reliable database of 2D aerodynamic coefficients was generated by establishing a robust methodology for numerical solution. A detailed range of heights above ground and angles of attack were included. Three discrete profiles were analysed and this comprehensive methodology should be easily applied to additional profiles in the future. Detailed analysis of this data was used to investigate theoretical concepts relating to GE stability. This objective was completed satisfactorily.
- c. **The third objective was to establish a simple yet reliable experimental technique for testing wing profiles IGE.** Due to the complexities and significant errors found in GE wind tunnel experiments, an alternative method that was simple yet able to better capture near-surface flow physics was developed. This method was used to validate numerical data in this case but the scope could be expanded for further work. A wing profile towed near the bottom surface of a water-filled towing tank was found to produce lift forces in agreement with 2D numerical predictions once adjusted for non-zero spanwise flow.

It can therefore be assumed that this method replicates the physics and flow patterns of a wing in air moving at low speed over static ground. This objective was completed satisfactorily.

- d. **The final objective was to develop a multi-variable parametric tool to generate viable configurations based on specified input criteria.** This purpose of the tool would be to explore the design space and assess feasibility of various configurations in a quantitative manner. Primary components were sized and positioned with corresponding performance and powering estimates, to generate and assess WIG conceptual designs. Conventional wing plus tail as well as tailless arrangements can be generated and analysed for static stability. The aero- and hydrodynamic performance data compiled from the first and second objectives was utilised to populate the model. A sample WIG was generated and checked against an established efficiency benchmark to determine suitability. This objective was completed satisfactorily.

6.2.2 Contributions to Design Methodologies

- i. **This work established a robust methodology for numerical solutions to create a systematic database of 2D aerodynamic coefficients.** Technical details for consistent grid topologies were investigated with sensitivity analyses for critical factors such as domain extents and mesh refinement. A robust scripting routine to import profiles at specified offsets and discretise the domain satisfactorily and repeatably was created to provide a large number of reliable numerical results to populate the design space. The methodology can be applied to additional profiles for future work.
- ii. **A RANS CFD code produced reliable aerodynamic coefficients with good spatial convergence and minimal discretisation errors, with appropriate turbulence model and y^+ values in the inflation layer.** Potential flow codes have been used by researchers and are useful for some aspects of WIG design but cannot accurately replicate the flow physics, resulting in modelling errors. As CFD methods capture the viscous interactions directly in the near-wall region,

these should be preferred. One drawback has been consistency of solution convergence across the full range of angles and heights above the surface.

- iii. **The parametric geometry tool has been applied to successfully generate conceptual configurations for WIG craft of the long-chord type.** This model is based upon design relationships of the primary components (i.e. hull, wing, machinery, etc.) and whether configurations might prove stable or require tail surfaces for safe operation. Weight groups have been assigned to assess effects of structural weight of hull and wing, payload, etc. Incorporating design concepts similar to flying wing and BWB aircraft, a compact WIG craft can be produced minimising structural vulnerabilities. A tailless configuration would be ideal for reducing weight aft, aerodynamic drag, and the probability of structural failures, but in most configurations the profiles tested would still require additional control surfaces.

6.2.3 Contributions to New Data

- i. **The theorised concept of a specific aerodynamic centre in height for GE airfoils was not found to exist on three different profiles.** The position of this neutral point has been stated to be instrumental in assessment of longitudinal stability characteristics via mathematical model. No stable chordwise position was observed. However, the aerodynamic centre in pitch was analytically identified for each of the profiles at a relatively stable position, with small rearwards movements at the lowest heights. Further investigation is recommended utilising an unsteady code, particularly in the regions of uncertainty $\alpha \leq 3^\circ$, to determine if this absence is the result of an inherent modelling anomaly caused by vortex shedding or other flow instability at the given Reynolds number.
- ii. **A rectangular plank wing (zero sweep, zero taper) utilising either of the tested NACA profiles will be fundamentally unstable without additional control surfaces, although in some cases careful sizing and longitudinal positioning of the DHMTU profile should prove satisfactory.** This may be mitigated to some degree by the inclusion of a tail surface or it may be that a more

complex 3D geometry would prove more beneficial. The SSM can be calculated for various configurations and weight distributions to tailor stability characteristics to intended usage criteria.

- iii. **The effect of Reynolds number on the DHMTU profile was found to be within the experimental margins of error for $0.45 \times 10^6 \leq Re \leq 1.05 \times 10^6$.** A slight increase of lift coefficient was measured at $\alpha = 4^\circ$ and $\alpha = 8^\circ$, of up to $\sim 10\%$. This increase was not consistent across the full range of heights and should be considered negligible at this stage. At larger AoA tank effects seem to interfere as height above ground increases.
- iv. **Performance of the slender hull at the tested speeds and angles effectively becomes a planing craft similar to a zero-deadrise flat plate and for future development could benefit from design features such as chines or spray rails to deflect flow away from the hull sides.** This type of hullform may be suitable for very slender geometries in multihull configurations but would not be appropriate for moderate values of L/B. The model hull showed potential to perform well, although the results should be considered inconclusive at this stage. Further testing of this hullform at additional angle of incidence, including the possible addition of hard chine, strakes or spray rails, should show this hull to function well at take-off speeds as well as at waterborne lower speeds.

6.2.4 Contributions to Data Validation Methods

- i. **The novel method of WIG testing on the bottom of a water tank can be a successful and relatively low-cost method to confirm magnitude of forces IGE.** Favourable differences in the kinematic viscosities of air and water result in Reynolds number similarities at the lower speeds found in marine towing tanks. For GE work at low Mach number, there is no need to explicitly model the ground surface interactions as inherent flow physics are represented more accurately than complex wind tunnel methods. Careful consideration of tip boundary clearances to minimise 3D effects such as spanwise flow and circulation effects at certain speeds and angles is necessary if correlation to 2D coefficients is desired.

Sufficient water depth should be ensured to maintain consistency and accuracy of results, which may be difficult to achieve unless the tank is very deep, especially when testing at higher AoA where force and moments are at their greatest.

ii. **The newly-developed computational tool for generating 2D aerodynamic coefficients can be used to validate experimental results and test calibration.**

The flexibility to input profile coordinates at any given orientation and freestream flow speeds offers a rapid method to verify expected forces and moments at any given angle or height, including detailed surface phenomena such as localised pressures and laminar-to-turbulent transitional locations. Reliable experimental GE data is currently scarce, and often found to be erroneous, so this tool provides much-needed capability.

6.3 Further Work

As the field of WIG research is so sparsely populated, there are innumerable topics from fundamental phenomena to detailed specifics of design that are left to explore. The following list is by no means exhaustive but may provide inspiration for an intrepid researcher to continue some of the themes presented in this work.

- Development of the geometry model to include additional capability for quasi-static analysis during transition phases such as take-off. Inclusion of control surfaces in canard positions, in addition to the aft tail configuration. Additional testing of profiles with flaps deployed to determine if control surfaces on the main wing itself could reduce the necessity for an external tail or canard. Manipulation of 3D geometries to effect favourable performance should be investigated, specifically concentrating on modification to planform, such as sweep, taper and twist effects to modify localised angle of incidence.
- Further testing of the slender hull model over a broader range of angles of incidence. If found to have acceptable performance, the inclusion of a hard chine or spray rails to reduce topside wetting and provide additional lift. Additionally, modifying the model constraints to include freedom in heave and pitch would be advisable.
- Confirmation of aerodynamic characteristics in the GE region $\bar{h} \leq 0.3$, for NACA 25112 and DHMTU profiles, to determine accuracy of RANS solutions versus fundamentally unsteady fluid flow.
- Expansion of the database to include reliable aerodynamic coefficients for other suitable profiles IGE. This would advance WIG craft design capability and may lead to more-optimal configurations.

- Continuation of the database of aerodynamic coefficients for the DHMTU 10-40.2-10.2-60.21.5 profile that includes a TE flap to compare ACP and ACH movement IGE, and further development of the database of aerodynamic coefficients for any other profile that looks promising IGE or to confirm theoretical data.
- Investigation of the fundamental mechanism that results in rearward ACH positions being accompanied by positive pitching moments, and conversely forward ACH accompanied by negative moments. This is currently not well understood, and if progress can be made to deconstruct the mechanism, methods to mitigate can be developed.
- Following on from the previous point, a specialist airfoil design project could be carried out to determine feasibility of designing a profile that not only demonstrates predictable lift and moment characteristics throughout the GEZ but also can maintain a forward ACH position.
- Wing-in-tank testing with more sophisticated set up, including pressure taps on upper and lower surfaces, and some method of flow visualisation even if only supplying qualitative data to observe flow patterns.

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8 Appendices

8.1 Appendix – Selected WIG Designs

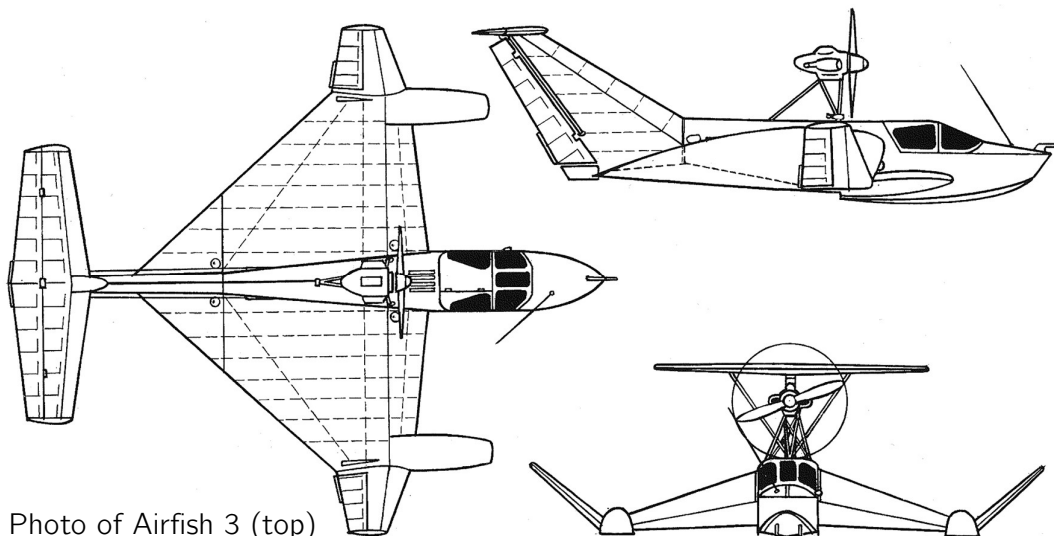
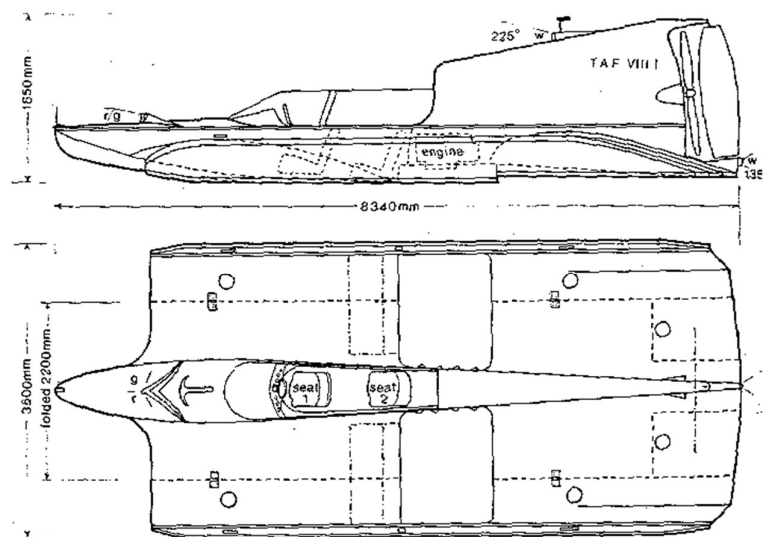
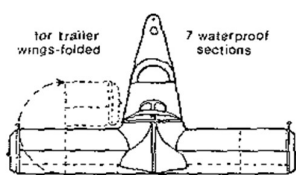


Photo of Airfish 3 (top)
3-view drawing of Airfish 8 (bottom)



Jörg Sport-fly

Photo & 3-view drawing of Jorg Flairboat

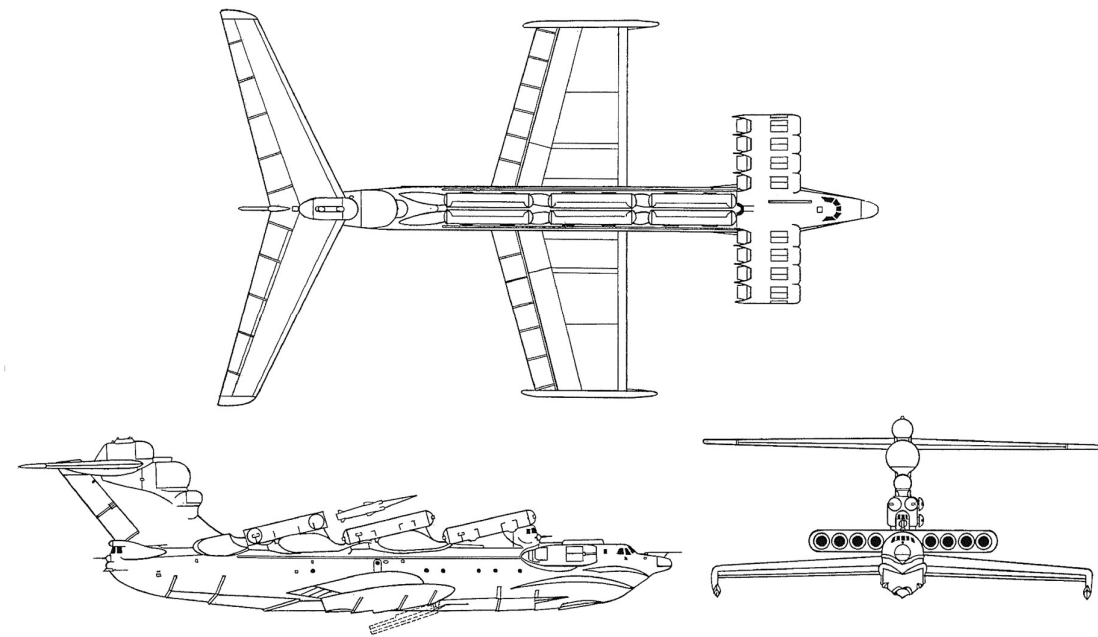


Photo & 3-view drawing of Lun

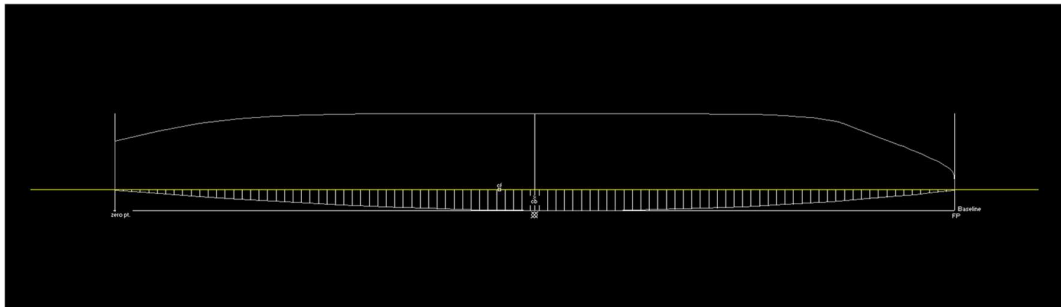
8.2 Appendix – WIG Vessel Particulars

	Length m	Span m	Height m	MTOW kg	Vol m ³	Power kW	Thrust kN	Vcr km/h	Fnv cr -	Vmax km/h	Fnv max -	Pax no.	Year	Country
SM-1	20.0	4.5	3.15	2830	2.761			170	12.73	270	20.22	-	1961	USSR
SM-2P	20.0	5.25	3.4	3200	3.122		17.6	170	12.47	270	19.81	-	1962	USSR
SM-3	14.5	3.8	2.8	3400	3.317		8.8	160	11.62	180	13.07	-	1962	USSR
SM-4	20.0	7.5	3.6	4800	4.683		28.5	200	13.71	230	15.77	-	1963	USSR
SM-5	18.0	9.5	5.5	7300	7.122			200	12.79	230	14.71	-	1963	USSR
SM-6	31.0	14.8	7.9	26500	25.85	2800		300	15.47	350	18.05	-	1970	USSR
SM-2P7	19.4	9.4	3.5	6300	6.146			250	16.38	270	17.69	-	1964	USSR
SM-8	24.5	9.5	5.5	8100	7.902			200	12.57	220	13.83	-	1967	USSR
KM	92.4	37.8	21.8	544000	530.7		1030	430	13.40	500	15.59	-	1966	USSR
Orlyonok	58.1	31.5	15.9	140000	136.6	11000	255	375	14.66	400	15.63	150	1972	USSR
Lun	73.8	44	19.2	380000	370.7		1020	450	14.89	550	18.20	170	1987	USSR
Spasatel	73.8	44	19.2	390000	380.5			450	14.83	550	18.12	500	2001	USSR
Volga-2	11.4	7.5		2500	2.439	206		120	9.17			8	1986	Russia
E-Volga-2	15	12.5	4.7	3300	3.220	224		150	10.95	200	14.60	10	1998	Russia
Amphistar														
X-113	8.43	5.9	2.0	360	0.351	36		80	8.45			-	1970	Germany
X-114	12.83	8.8	2.9	1500	1.463	180		150	12.49			-	1977	Germany
Airfish 3-A	9.9	8.6	2.6	700	0.683	67		120	11.34	-	-			Germany
TAF VIII-4	18	7.19	4.05	4600	4.488	560		170	11.74	-	-			Germany
FS8 Dragon	17.45	15.6	4.1	4750	4.634	338		158	10.85	-	-			Australia
Radacraft	10.1	8.5	-	1950	1.902	224		185	14.76	241	19.18			Australia
Swan	19.04	13.4	5.2	7500	7.317	514		140	8.91			20	1997	China
Xiangzhou 1	12.7	11.0	3.9	2500	2.439			150	11.47	210	16.05			China

8.3 Appendix – Hull Model Design Data

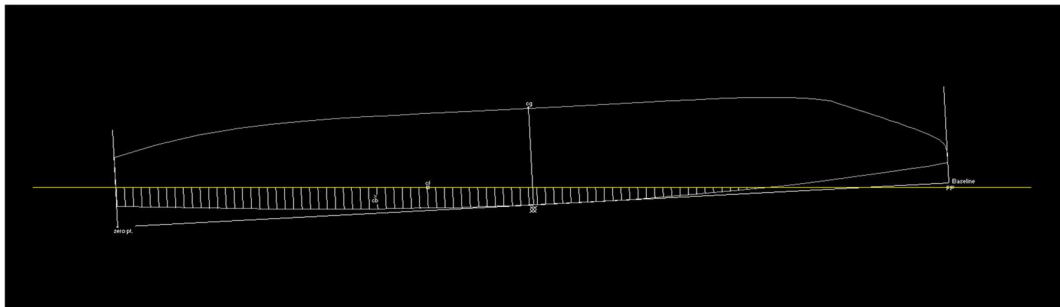
0° Trim

Draft Amidships m	0.000	0.005	0.010	0.015	0.020	0.025	0.030	0.035	0.040	0.045	0.050	0.055	0.060	0.065	0.070	0.075
Displacement kg	0	0.1441	0.648	1.513	2.719	4.232	6.01	8.019	10.23	12.62	15.18	17.89	20.74	23.72	26.8	29.99
Heel to Starboard degrees	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Draft at FP m	0	0.005	0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075
Draft at AP m	0	0.005	0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075
Draft at LCF m	0	0.005	0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075
Trim (+ve by stern) m	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WL Length m	0	0.753	1.068	1.314	1.523	1.707	1.874	2.03	2.175	2.312	2.445	2.57	2.693	2.81	2.922	3
WL Beam m	0	0.112	0.164	0.198	0.218	0.229	0.234	0.236	0.238	0.239	0.24	0.24	0.241	0.242	0.242	0.243
Wetted Area m^2	0	0.063	0.135	0.205	0.271	0.33	0.385	0.436	0.486	0.536	0.583	0.631	0.676	0.723	0.769	0.811
Waterpl. Area m^2	0	0.063	0.134	0.203	0.266	0.322	0.37	0.412	0.449	0.484	0.514	0.543	0.568	0.592	0.613	0.628
Prismatic Coeff.	0	0.553	0.57	0.577	0.582	0.588	0.594	0.598	0.602	0.605	0.606	0.607	0.607	0.607	0.606	0.611
Block Coeff.	0	0.335	0.361	0.379	0.4	0.423	0.446	0.466	0.483	0.496	0.506	0.514	0.52	0.525	0.528	0.536
Midship Area Coeff.	0	0.606	0.633	0.657	0.687	0.719	0.753	0.783	0.806	0.826	0.841	0.854	0.865	0.874	0.882	0.889
Waterpl. Area Coeff.	0	0.746	0.765	0.781	0.802	0.824	0.844	0.859	0.869	0.877	0.878	0.879	0.875	0.872	0.866	0.863
LCB from zero pt. (+ve fwd) m	0	1.613	1.608	1.604	1.599	1.595	1.59	1.583	1.576	1.568	1.559	1.549	1.539	1.527	1.514	1.501
LCF from zero pt. (+ve fwd) m	0	1.61	1.603	1.598	1.591	1.583	1.572	1.558	1.543	1.523	1.506	1.482	1.461	1.431	1.4	1.373
KB m	0	0.004	0.007	0.01	0.013	0.017	0.02	0.023	0.026	0.029	0.032	0.035	0.038	0.041	0.044	0.047
KG m	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
BMT m	0	0.354	0.359	0.342	0.312	0.275	0.238	0.206	0.18	0.159	0.141	0.127	0.115	0.105	0.097	0.089
BML m	0	14.213	14.326	14.397	14.507	14.576	14.644	14.654	14.646	14.721	14.577	14.545	14.322	14.184	13.88	13.31
GMT m	0.462	0.008	0.016	0.002	-0.024	-0.058	-0.092	-0.121	-0.144	-0.162	-0.176	-0.187	-0.196	-0.203	-0.209	-0.213
GML m	0.462	13.866	13.983	14.057	14.171	14.243	14.314	14.327	14.322	14.401	14.259	14.231	14.011	13.876	13.574	13.008
KMT m	0.812	0.358	0.366	0.352	0.326	0.292	0.258	0.229	0.206	0.188	0.174	0.163	0.154	0.147	0.141	0.137
KML m	0.812	14.216	14.333	14.407	14.521	14.593	14.664	14.677	14.672	14.751	14.609	14.581	14.361	14.226	13.924	13.358
Immersion (TPC) tonne/cm	0	0.001	0.001	0.002	0.003	0.003	0.004	0.004	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.006
MTc tonne.m	0	0	0	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0.001
RM at 1deg = GMT.Disp.sin(1) kg.m	0	0	0	0	-0.001	-0.004	-0.01	-0.017	-0.026	-0.036	-0.047	-0.059	-0.071	-0.084	-0.098	-0.112
Max deck inclination deg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trim angle (+ve by stern) deg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



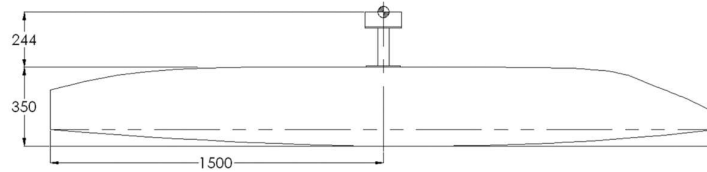
3° Trim

Draft Amidships m	0.000	0.004	0.008	0.013	0.017	0.021	0.025	0.029	0.033	0.038	0.042	0.046	0.050	0.054	0.058	0.063
Displacement kg	2.284	3.533	4.918	6.415	8.008	9.688	11.44	13.27	15.17	17.13	19.14	21.22	23.34	25.52	27.74	30.01
Heel to Starboard degrees	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Draft at FP m	-0.079	-0.074	-0.07	-0.066	-0.062	-0.058	-0.053	-0.049	-0.045	-0.041	-0.037	-0.033	-0.028	-0.024	-0.02	-0.016
Draft at AP m	0.079	0.083	0.087	0.091	0.095	0.099	0.104	0.108	0.112	0.116	0.12	0.124	0.129	0.133	0.137	0.141
Draft at LCF m	0.043	0.045	0.047	0.049	0.051	0.053	0.056	0.058	0.061	0.064	0.067	0.07	0.073	0.076	0.079	0.082
Trim (+ve by stern) m	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157	0.157
WL Length m	1.49	1.58	1.66	1.732	1.799	1.862	1.92	1.975	2.028	2.078	2.126	2.172	2.216	2.259	2.3	2.341
WL Beam m	0.209	0.221	0.228	0.232	0.234	0.236	0.237	0.238	0.239	0.24	0.24	0.241	0.242	0.242	0.243	0.243
Wetted Area m^2	0.278	0.318	0.352	0.384	0.415	0.445	0.474	0.503	0.531	0.559	0.587	0.615	0.643	0.67	0.698	0.726
Waterpl. Area m^2	0.274	0.309	0.338	0.362	0.383	0.402	0.42	0.436	0.451	0.465	0.479	0.491	0.503	0.515	0.526	0.536
Prismatic Coeff.	0.692	0.714	0.724	0.73	0.734	0.737	0.739	0.741	0.742	0.743	0.744	0.744	0.744	0.744	0.744	0.743
Block Coeff.	0.481	0.519	0.546	0.569	0.587	0.601	0.614	0.624	0.632	0.639	0.645	0.65	0.654	0.658	0.661	0.663
Midship Area Coeff.	0.699	0.727	0.756	0.783	0.805	0.824	0.839	0.851	0.86	0.868	0.875	0.881	0.886	0.891	0.894	0.898
Waterpl. Area Coeff.	0.882	0.887	0.895	0.902	0.909	0.915	0.921	0.926	0.93	0.934	0.936	0.938	0.94	0.94	0.941	0.941
LCB from zero pt. (+ve fwd) m	0.654	0.67	0.692	0.715	0.737	0.759	0.78	0.8	0.82	0.838	0.856	0.873	0.889	0.905	0.92	0.935
LCF from zero pt. (+ve fwd) m	0.674	0.723	0.768	0.809	0.846	0.88	0.911	0.94	0.968	0.993	1.018	1.041	1.063	1.083	1.104	1.122
KB m	0.039	0.041	0.042	0.044	0.045	0.046	0.047	0.049	0.05	0.052	0.053	0.055	0.056	0.058	0.059	0.061
KG m	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
BMT m	0.39	0.319	0.268	0.23	0.201	0.179	0.161	0.146	0.134	0.123	0.114	0.107	0.1	0.094	0.089	0.084
BML m	19.421	16.009	13.954	12.591	11.612	10.872	10.286	9.807	9.404	9.06	8.768	8.499	8.274	8.055	7.876	7.687
GMt m	0.035	-0.033	-0.081	-0.117	-0.143	-0.164	-0.179	-0.191	-0.201	-0.209	-0.216	-0.221	-0.225	-0.229	-0.232	-0.235
GML m	19.067	15.657	13.604	12.244	11.268	10.53	9.946	9.47	9.069	8.728	8.437	8.171	7.949	7.732	7.555	7.369
KMt m	0.429	0.36	0.31	0.274	0.246	0.225	0.208	0.195	0.184	0.175	0.168	0.161	0.156	0.152	0.148	0.145
KML m	19.461	16.05	13.996	12.635	11.657	10.918	10.333	9.856	9.455	9.112	8.821	8.553	8.33	8.113	7.935	7.748
Immersion (TPC) tonne/cm	0.003	0.003	0.003	0.004	0.004	0.004	0.004	0.004	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
MTC tonne.m	0	0	0	0	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001
RM at 1deg = GMt.Disp.sin(1) kg.m	0.001	-0.002	-0.007	-0.013	-0.02	-0.028	-0.036	-0.044	-0.053	-0.063	-0.072	-0.082	-0.092	-0.102	-0.112	-0.123
Max deck inclination deg	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Trim angle (+ve by stern) deg	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0



8.4 Appendix – Hull Model Test Data

drag = positive aft
lift = positive upwards
pitching moment = positive nose up



note: all values given with respect to origin as marked

Percent displacement	0.267	0.506	0.791	1.000
Draft Amidsh. m	0.035	0.050	0.065	0.075
Displacement kg	8.019	15.18	23.72	29.99

0 DEGREE TRIM												
speed m/s	27% disp			50% disp			79% disp			100% disp		
	drag N	lift N	p.mom Nm	drag N	lift N	p.mom Nm	drag N	lift N	p.mom Nm	drag N	lift N	p.mom Nm
1										2.1	-5.2	1.4
2										6.9	-20.3	-2.2
3										18.1	-50.5	-39.0
4										29.2	-52.1	-50.6
5							36.0	-56.7	-48.7	41.3	-65.3	-56.7
6							46.2	-86.5	-47.0	53.4	-102.8	-61.1
7				47.4	-83.2	-21.4	61.5	-103.8	-41.5	72.8	-112.5	-53.4
8				67.7	-82.9	-21.8	87.8	-103.9	-33.7	102.9	-108.1	-35.6
9	73.5	-67.7	-4.0	93.6	-83.8	-20.4	121.0	-102.2	-24.6	140.3	-130.5	-20.9
10	93.9	-89.2	-4.6	121.6	-117.1	-20.2	157.8	-136.2	-18.1	172.0	-126.8	-1.9
11	120.7	-112.5	-7.3	154.8	-130.9	-23.2	201.8	-144.8	-14.7	243.3	-185.2	8.5
12	148.7	-124.8	-12.0	194.8	-167.1	-30.6	253.1	-190.3	-21.3	305.7	-237.7	-7.1

Percent displacement	0.509	0.802	1.000
Draft Amidsh. m	0.059	0.068	0.078
Displacement kg	15.27	24.06	30.01

3 DEGREE TRIM									
speed m/s	50% disp			80% disp			100% disp		
	drag N	lift N	p.mom Nm	drag N	lift N	p.mom Nm	drag N	lift N	p.mom Nm
1									
2									
3									
4							33.0	-4.7	-59.0
5				42.7	-8.5	-62.8	45.8	-12.0	-65.2
6				56.0	-40.7	-77.0	59.6	-23.6	-72.6
7				73.9	-46.1	-88.0	77.7	-38.5	-86.1
8				98.3	-42.7	-98.2	104.7	-44.9	-104.4
9	122.0	-44.0	-98.9	128.9	-44.5	-111.3	135.6	-44.6	-118.7
10	150.2	-49.7	-125.9	165.2	-49.1	-131.8	168.9	-47.1	-146.8
11	176.9	-71.1	-163.4	207.2	-61.5	-160.9	205.8	-66.2	-181.9
12	222.3	-97.4	-190.5	247.1	-82.1	-202.9	249.9	-82.3	-225.6

8.5 Appendix – DHMTU Profile Coordinates

x	y_upper	y_lower	x	y_upper	y_lower
0.000000	0.000000	0.000000	0.175000	0.072412	-0.020000
0.000391	0.002174	-0.001753	0.200000	0.078067	-0.020000
0.000781	0.003043	-0.002589	0.225000	0.083084	-0.020000
0.001172	0.003732	-0.003244	0.250000	0.087505	-0.020000
0.001563	0.004328	-0.003805	0.275000	0.091303	-0.020000
0.002344	0.005362	-0.004762	0.300000	0.094419	-0.020000
0.003125	0.006271	-0.005579	0.325000	0.096832	-0.020000
0.003906	0.007105	-0.006305	0.350000	0.098561	-0.020000
0.004688	0.007890	-0.006960	0.375000	0.099620	-0.020000
0.005469	0.008632	-0.007554	0.400000	0.100000	-0.020000
0.006250	0.009336	-0.008096	0.425000	0.099727	-0.020000
0.007031	0.010004	-0.008591	0.450000	0.098827	-0.020000
0.007813	0.010640	-0.009044	0.475000	0.097382	-0.020000
0.008594	0.011247	-0.009461	0.500000	0.095454	-0.020000
0.009375	0.011828	-0.009845	0.525000	0.093077	-0.020000
0.010156	0.012386	-0.010202	0.550000	0.090280	-0.020000
0.010938	0.012924	-0.010533	0.575000	0.087072	-0.020000
0.011719	0.013443	-0.010844	0.600000	0.083447	-0.019994
0.012500	0.013948	-0.011136	0.625000	0.079430	-0.019958
0.014063	0.014919	-0.011676	0.650000	0.075104	-0.019909
0.015625	0.015855	-0.012176	0.675000	0.070548	-0.019852
0.017188	0.016771	-0.012653	0.700000	0.065766	-0.019724
0.018750	0.017669	-0.013110	0.725000	0.060729	-0.019436
0.020313	0.018552	-0.013547	0.750000	0.055465	-0.018953
0.021875	0.019419	-0.013966	0.775000	0.050052	-0.018298
0.025000	0.021108	-0.014749	0.800000	0.044555	-0.017466
0.031250	0.024322	-0.016102	0.825000	0.038993	-0.016410
0.037500	0.027333	-0.017184	0.850000	0.033379	-0.015091
0.043750	0.030164	-0.018018	0.875000	0.027714	-0.013496
0.050000	0.032845	-0.018644	0.900000	0.022022	-0.011585
0.056250	0.035405	-0.019102	0.925000	0.016361	-0.009280
0.062500	0.037872	-0.019432	0.937500	0.013556	-0.007976
0.068750	0.040269	-0.019665	0.950000	0.010776	-0.006577
0.075000	0.042599	-0.019822	0.962500	0.008024	-0.005094
0.081250	0.044866	-0.019919	0.975000	0.005304	-0.003534
0.087500	0.047069	-0.019971	0.981250	0.003955	-0.002714
0.093750	0.049211	-0.019996	0.987500	0.002613	-0.001856
0.100000	0.051292	-0.020000	0.990625	0.001947	-0.001411
0.106250	0.053316	-0.020000	0.992188	0.001616	-0.001184
0.112500	0.055285	-0.020000	0.993750	0.001288	-0.000953
0.118750	0.057202	-0.020000	0.995313	0.000962	-0.000719
0.125000	0.059069	-0.020000	0.996875	0.000640	-0.000482
0.137500	0.062663	-0.020000	0.998438	0.000319	-0.000242
0.150000	0.066083	-0.020000	1.000000	0.000000	0.000000

8.6 Appendix – ICEM Scripting

```
#load coordinate text file from location#
ic_geo_cre_geom_input <filename_here.txt> 0.001 input PNTS pnt CRVS crv SURFS
srf
ic_boco_solver
ic_boco_clear_icons
ic_csystem_display all 0
ic_csystem_set_current global
ic_boco_nastran_csystem reset
ic_geo_new_family GEOM
ic_boco_set_part_color GEOM

#define domain extents#
ic_point {} GEOM pnt.00 <x_min_coord>,<y_min_coord>,0
ic_point {} GEOM pnt.01 <x_min_coord>,<y_max_coord>,0
ic_point {} GEOM pnt.02 <x_max_coord>,<y_max_coord>,0
ic_point {} GEOM pnt.03 <x_max_coord>,<y_min_coord>,0

#name definition for boundaries#
ic_geo_new_family INLET
ic_boco_set_part_color INLET
ic_delete_geometry curve names crv.00 0
ic_curve point INLET crv.00 {pnt.00 pnt.01}
ic_geo_new_family TOP
ic_boco_set_part_color TOP
ic_delete_geometry curve names crv.01 0
ic_curve point TOP crv.01 {pnt.01 pnt.02}
ic_geo_new_family OUTLET
ic_boco_set_part_color OUTLET
ic_delete_geometry curve names crv.02 0
ic_curve point OUTLET crv.02 {pnt.02 pnt.03}
ic_geo_new_family GROUND
ic_boco_set_part_color GROUND
ic_delete_geometry curve names crv.03 0
ic_curve point GROUND crv.03 {pnt.03 pnt.00}
ic_delete_geometry curve names crv.04 0
ic_curve point GROUND crv.04 {}
ic_geo_new_family DOMAIN
ic_boco_set_part_color DOMAIN
ic_surface 2-4crvs DOMAIN srf.00 {0.01 {crv.00 crv.01 crv.02 crv.03}}
ic_set_dormant_pickable point 0 {}
ic_set_dormant_pickable curve 0 {}
ic_hex_initialize_mesh 2d new_numbering new_blocking DOMAIN
ic_hex_switch_blocking root
ic_hex_unblank_blocks
ic_hex_multi_grid_level 0
```

```

ic_hex_projection_limit 0
ic_hex_default_bunching_law default 2.0
ic_hex_floating_grid off
ic_hex_transfinite_degree 1
ic_hex_unstruct_face_type one_tri
ic_hex_set_unstruct_face_method uniform_quad
ic_hex_set_n_tetra_smoothing_steps 20
ic_hex_set_mesh_params PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN -version 110
ic_hex_error_messages off_minor
ic_hex_switch_blocking root
ic_hex_set_edge_projection 11 13 0 1 crv.00
ic_hex_set_edge_projection 13 21 0 1 crv.01
ic_hex_set_edge_projection 19 21 0 1 crv.02
ic_hex_set_edge_projection 11 19 0 1 crv.03
ic_hex_project_to_surface DOMAIN INLET GEOM OUTLET PNTS CRVS
GROUND TOP SURFS

#prelim element size parameters#
ic_geo_set_family_params CRVS no_crv_inf prism 0 emax 0.02 emin 0.0 edev 0.0
ic_geo_set_family_params GROUND no_crv_inf prism 0 emax 0.1 emin 0.0 edev 0.0
ic_geo_set_family_params INLET no_crv_inf prism 0 emax 0.1 emin 0.0 edev 0.0
ic_geo_set_family_params OUTLET no_crv_inf prism 0 emax 0.1 emin 0.0 edev 0.0
ic_geo_set_family_params TOP no_crv_inf prism 0 emax 0.1 emin 0.0 edev 0.0
ic_geo_params_blank_done part 1

#split domain into blocks#
ic_hex_split_grid 11 13 0.18 m PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN VORFN
ic_hex_split_grid 11 19 0.44 m PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN VORFN
ic_hex_mark_blocks unmark
ic_hex_mark_blocks superblock 13
ic_hex_mark_blocks numbers 19 34 edge_neighbors
ic_hex_ogrid 1 m PNTS CRVS SURFS GEOM INLET TOP OUTLET GROUND
DOMAIN -version 50
ic_hex_mark_blocks unmark
ic_hex_mark_blocks unmark

#split block at trailing edge#
ic_hex_split_grid 41 43 pnt201 m PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN VORFN
ic_hex_mark_blocks unmark
ic_hex_mark_blocks superblock 13
ic_hex_change_element_id VORFN
ic_hex_set_edge_projection 42 51 0 1 crv0
ic_hex_project_to_surface 42 51
ic_hex_set_edge_projection 41 49 0 1 crv1

```

```

ic_hex_project_to_surface 41 49
ic_hex_set_mesh_params PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN -version 110
ic_hex_compute_mesh_size PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN
ic_hex_undo_major_start auto_edge_split
ic_hex_auto_split_edge 42 51
ic_hex_undo_major_end auto_edge_split
ic_hex_undo_major_start auto_edge_split
ic_hex_auto_split_edge 41 49
ic_hex_undo_major_end auto_edge_split
ic_hex_create_composite {crv0 crv1}
ic_hex_set_edge_projection 41 42 0 1 crv0
ic_hex_project_to_surface 41 42

#locate splits normal to airfoil surfaces#
ic_hex_place_node 42 curve:crv0 0.97
ic_hex_place_node 41 curve:crv1 0.02
ic_hex_place_node 51 curve:crv0 0.00001
ic_hex_place_node 49 curve:crv0 0.00001
ic_hex_place_node 48 curve:crv.03 0.46
ic_hex_align_vertices 0 2 1 0 0 -csys global PNTS CRVS SURFS GEOM INLET TOP
OUTLET GROUND DOMAIN

#aft upper point location to follow upper surface contour#
ic_hex_set_node_location dx .25 dy -0.10 -csys global node_numbers {{ 50 }}
ic_hex_place_node 52 curve:crv.01 0.56
ic_hex_mark_blocks unmark
ic_hex_mark_blocks superblock 24
ic_hex_collapse_blocks 1 version 410
ic_hex_move_node 51 pnt201
ic_hex_get_node_location { 51 } _temp_x _temp_y _temp_z
ic_hex_set_node_location y {$ _temp_y} -csys global node_numbers {{ 44 }}
ic_hex_list_family_projection

#discretise edges to suit#
ic_hex_split_grid 38 42 0.99 m PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN VORFN
ic_hex_set_mesh 51 44 n 500 h1rel 0.000116666666667 h2rel 0.0 r1 1.01 r2 2 lmax 0
expl copy_to_parallel unlocked
ic_hex_set_mesh 38 50 n 200 h1rel 0.00367369565697 h2rel 0.000734737661918 r1
1.1 r2 1.05 lmax 0 default copy_to_parallel unlocked
ic_hex_set_mesh 58 42 n 20 h1rel 0.314225775953 h2rel 0.00916659900844 r1 2 r2
1.05 lmax 0 geo2 copy_to_parallel unlocked
ic_hex_set_mesh 38 58 n 150 h1rel 0.00179447981567 h2rel 0.00179447981567 r1 1.1
r2 1.05 lmax 0 default copy_to_parallel unlocked
ic_hex_match_edges 58 42 38 58

```

```

ic_hex_set_mesh 41 42 n 30 h1rel 0.12273914495 h2rel 0.12273914495 r1 1.2 r2 1.2
lmax 0 default copy_to_parallel unlocked
ic_hex_set_mesh 37 38 n 70 h1rel 0.0102880658436 h2rel 0.0102880658436 r1 1.2 r2
1.2 lmax 0 default copy_to_parallel unlocked
ic_hex_set_mesh 38 39 n 150 h1rel 0.000564588979223 h2rel 0.0336926377597 r1 1.1
r2 2 lmax 0 default copy_to_parallel unlocked
ic_hex_set_mesh 33 38 n 150 h1rel 0.0 h2rel 0.000174825174825 r1 2 r2 1.2 lmax 0
geo2 copy_to_parallel unlocked
ic_hex_set_mesh 42 51 n 150 h1rel 0.000989501390249 h2rel 0.000642784061112 r1
1.1 r2 1.05 lmax 0 default unlocked
ic_hex_set_mesh 58 59 n 150 h1rel 0.000989501390249 h2rel 0.000642786040114 r1
1.1 r2 1.05 lmax 0 default unlocked
ic_hex_set_mesh 54 55 n 150 h1rel 0.000989501390249 h2rel 0.000642786040114 r1
1.1 r2 1.05 lmax 0 default unlocked
ic_hex_set_mesh 41 51 n 150 h1rel 0.000989501390249 h2rel 0.000642786040114 r1
1.1 r2 1.05 lmax 0 default unlocked
ic_hex_set_mesh 39 52 n 100 h1 0.01 h2 0.001 r1 1.1 r2 1.05 lmax 0 default unlocked

```

#create mesh#

```

ic_hex_create_mesh PNTS CRVS SURFS GEOM INLET TOP OUTLET GROUND
DOMAIN proj 2 dim_to_mesh 3
ic_hex_write_file hex.uns PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN proj 2 dim_to_mesh 3 -family_boco family_boco.fbc
ic_uns_load hex.uns 3 0 {} 2
ic_uns_update_family_type visible {DOMAIN INLET GEOM OUTLET PNTS ORFN
CRVS GROUND TOP SURFS} {!NODE !LINE_2 QUAD_4} update 0
ic_uns_diag_reset_degen_min_max
ic_boco_solver
ic_uns_update_family_type visible {DOMAIN INLET GEOM OUTLET PNTS ORFN
CRVS GROUND TOP SURFS} {!NODE !LINE_2 QUAD_4} update 0
ic_boco_clear_icons
ic_csystem_display all 0
ic_csystem_set_current global
ic_boco_nastran_csystem reset
ic_uns_diag_reset_degen_min_max

```

#smoothing function#

```

ic_hex_ratio_histogram 20 PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN proj 2 minval 0 -type determinant_27 maxval 1 new_format
ic_hex_smooth 5 PNTS CRVS SURFS GEOM INLET TOP OUTLET GROUND
DOMAIN CREATED_FACES elliptic iter_srf 10 iter_vol 5 exp_srf 0.0 exp_vol 0.0
smooth_type 202 nfix_layers -1 fams_attr { GROUND 0 0 CRVS 0 0.00007}
rebunch_edges 0 treat_unstruct 0 stabilize_srf 1.0 stabilize_vol 2.0 ortho_distance_srf 0
ortho_distance_vol 0 surface_fitting 1 keep_per_geom 1
ic_uns_subset_delete smooth_show_map
ic_uns_diag_reset_degen_min_max
ic_uns_diag_reset_degen_min_max

```

```

ic_hex_ratio_histogram 20 PNTS CRVS SURFS GEOM INLET TOP OUTLET
GROUND DOMAIN proj 2 minval 0 -type determinant_27 maxval 1 new_format
ic_undo_group_begin
ic_boco_solver Fluent_V6
ic_solver_mesh_info Fluent_V6
ic_undo_group_end

#set bocos for mesh export to fluent#
ic_boco_set DOMAIN {{1 FLUID 0} { 1 {color} 14522931 }}
ic_boco_set GEOM { { 1 {color} 16663866 } }
ic_boco_set INLET {{1 VELI 0} { 1 {color} 16663101 }}
ic_boco_set OUTLET {{1 PRESO 0} { 1 {color} 3387852 }}
ic_boco_set ORFN {}
ic_boco_set PNTS {}
ic_boco_set CRVS {}
ic_boco_set GROUND { { 1 {color} 16661826 } }
ic_boco_set TOP {{1 SYM 0} { 1 {color} 14693271 }}
ic_boco_set SURFS {}
ic_geo_new_family VORFN 0
ic_uns_new_family VORFN 1
ic_boco_set VORFN {}

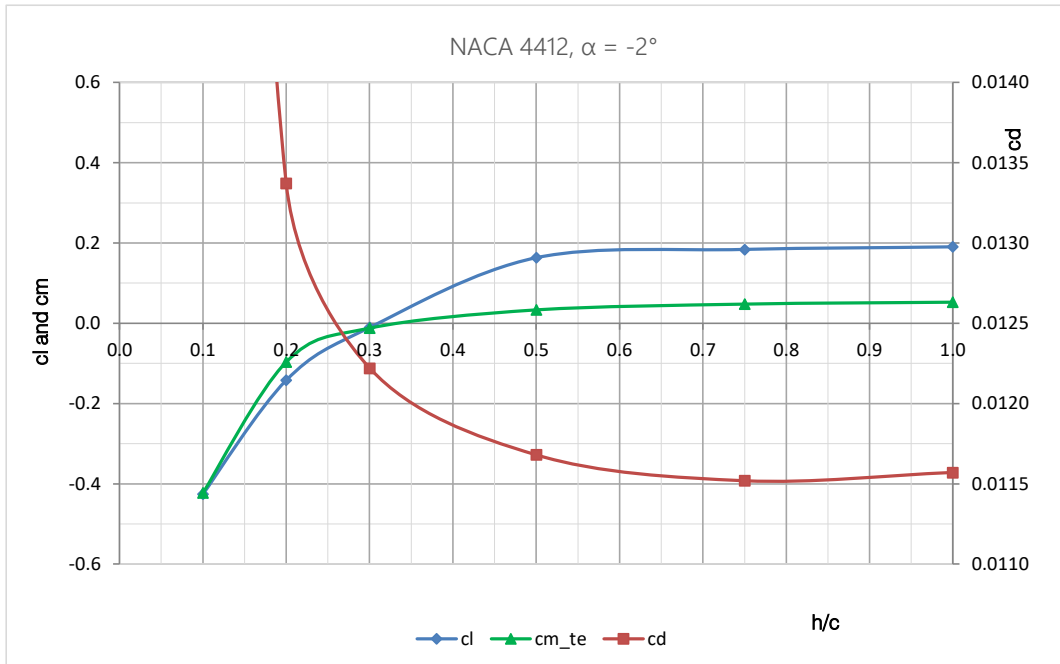
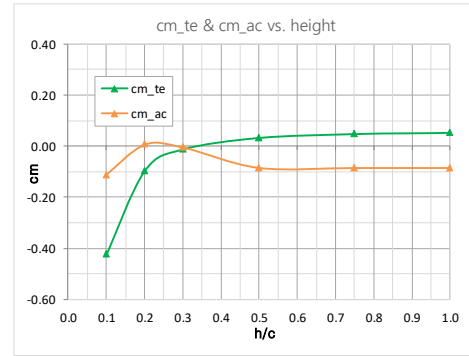
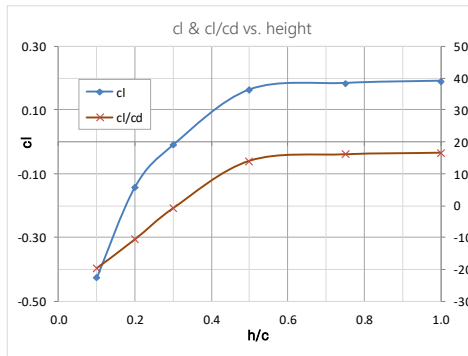
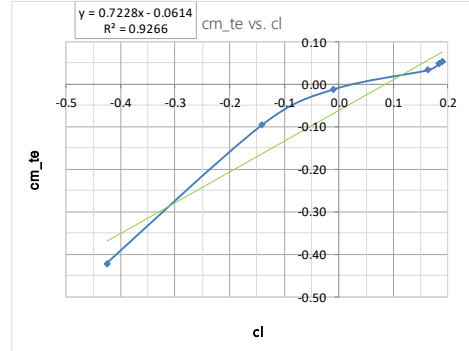
```

8.7 Appendix – Detailed Results NACA 4412

NACA 4412

alpha = -2 deg
x_ac = 0.730 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05						
0.1	-0.4255	0.02174	-0.4225	-19.6	-0.1119	-1.191
0.2	-0.1420	0.01337	-0.0966	-10.6	0.0071	-0.646
0.3	-0.0105	0.01222	-0.0121	-0.9	-0.0044	-0.052
0.5	0.1632	0.01168	0.0332	14.0	-0.0859	0.850
0.75	0.1838	0.01152	0.0479	16.0	-0.0863	0.971
1.0	0.1902	0.01157	0.0525	16.4	-0.0863	-
					mean =	-0.0613
					st. dev =	0.0496
					pct. =	0.810

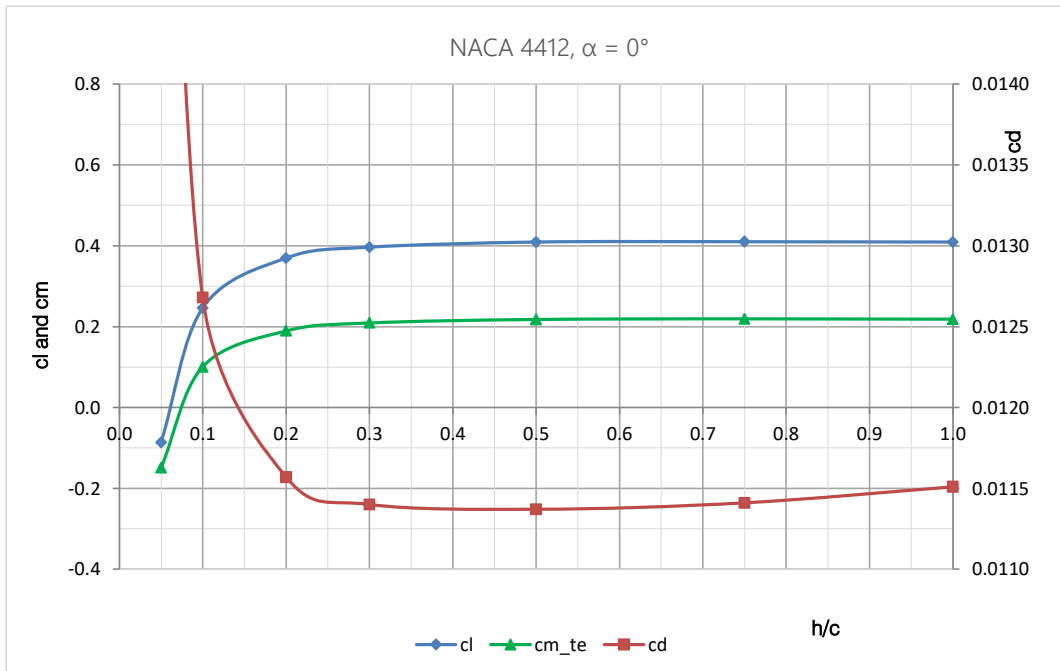
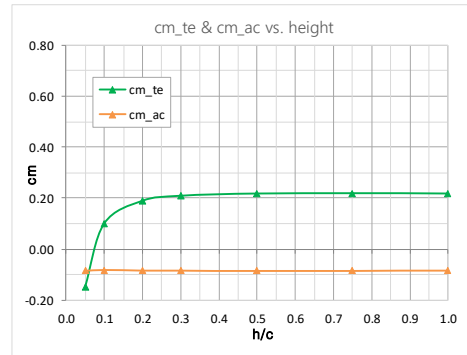
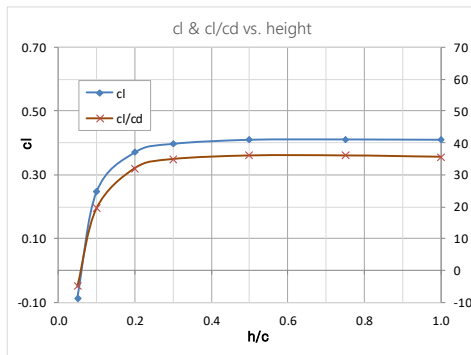
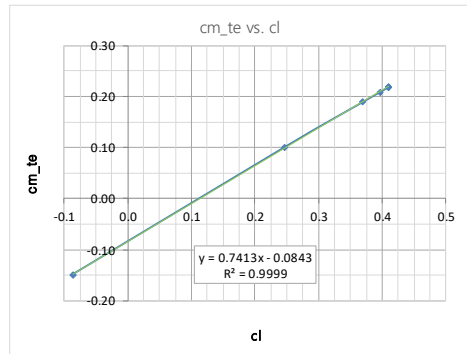


NACA 4412

alpha = 0 deg
x_ac = 0.741 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	-0.0864	0.01736	-0.1492	-5.0	-0.0852	-0.140
0.1	0.2461	0.01268	0.1007	19.4	-0.0817	0.546
0.2	0.3695	0.01157	0.1898	31.9	-0.0840	0.899
0.3	0.3966	0.01140	0.2092	34.8	-0.0847	0.979
0.5	0.4089	0.01137	0.2181	36.0	-0.0849	1.012
0.75	0.4103	0.01141	0.2193	36.0	-0.0847	1.012
1.0	0.4089	0.01151	0.2186	35.5	-0.0844	-

mean = -0.0842
st. dev = 0.0012
pct. = 0.014

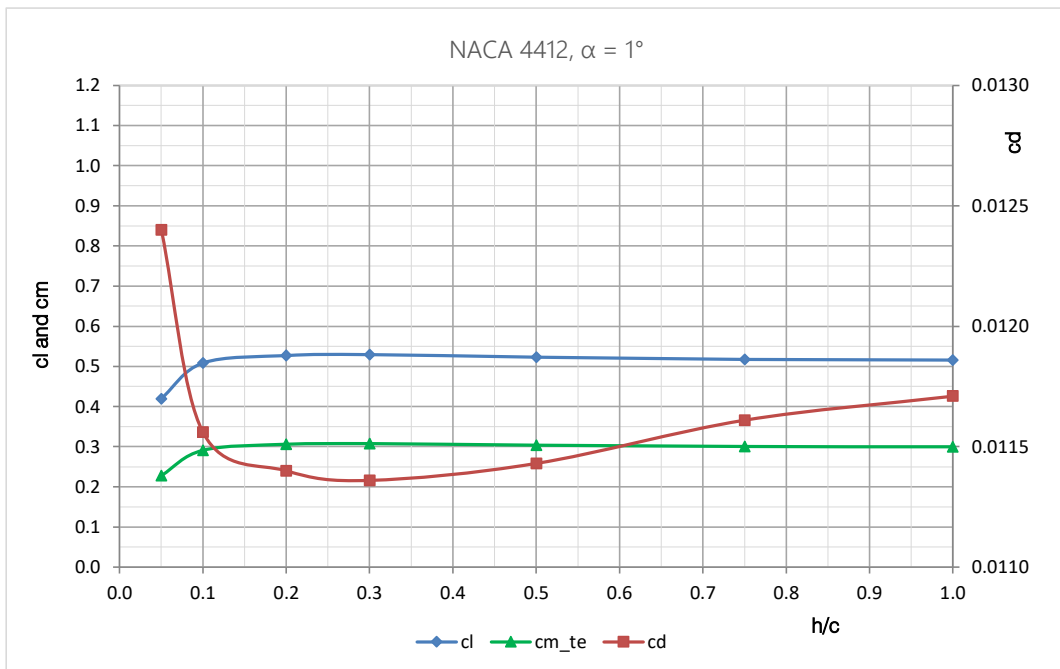
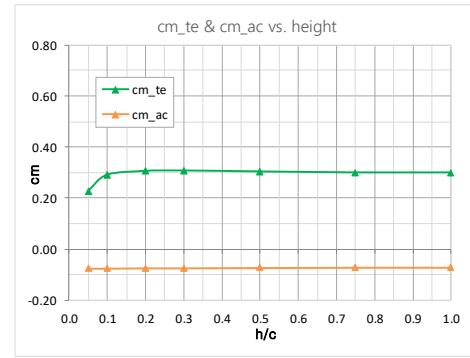
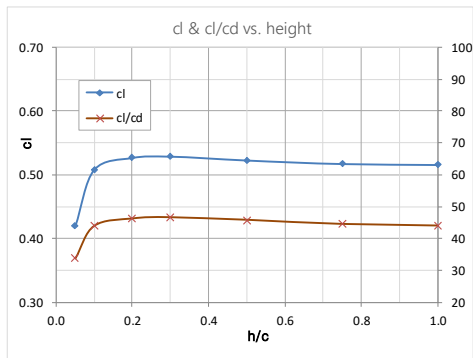
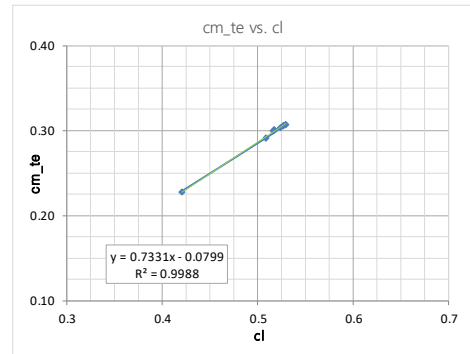


NACA 4412

alpha = 1 deg
x_ac = 0.720 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	0.4198	0.01240	0.2279	33.9	-0.0744	0.768
0.1	0.5082	0.01156	0.2913	44.0	-0.0746	0.998
0.2	0.5271	0.01140	0.3058	46.2	-0.0737	1.049
0.3	0.5290	0.01136	0.3074	46.6	-0.0735	1.057
0.5	0.5231	0.01143	0.3040	45.8	-0.0726	1.039
0.75	0.5174	0.01161	0.3006	44.6	-0.0719	1.011
1.0	0.5160	0.01171	0.2997	44.1	-0.0718	-

mean = -0.0732
st. dev = 0.0011
pct. = 0.015

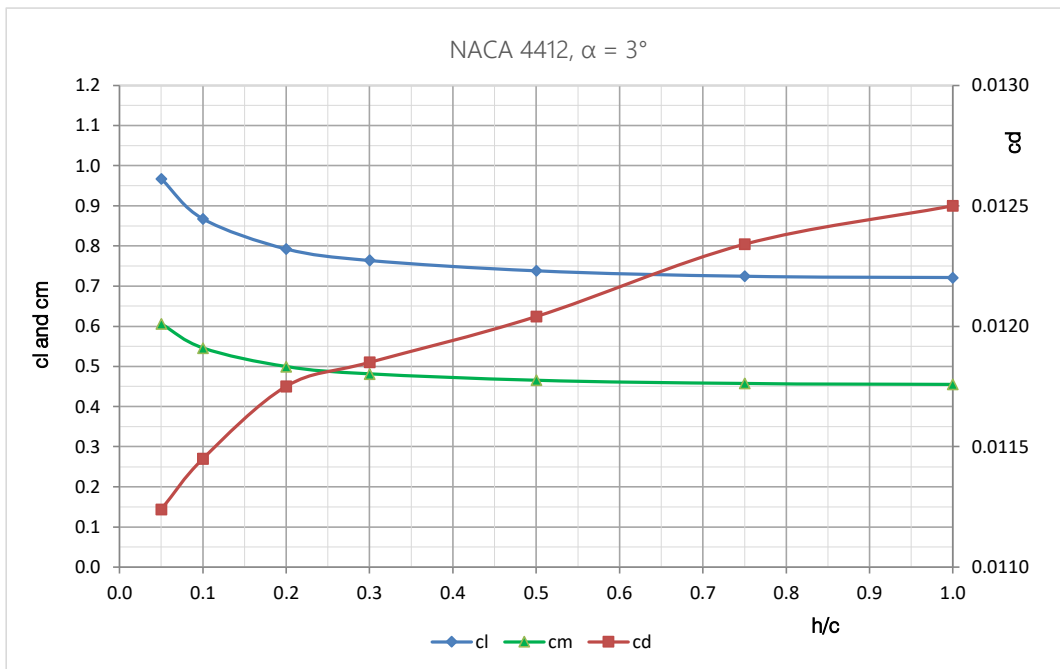
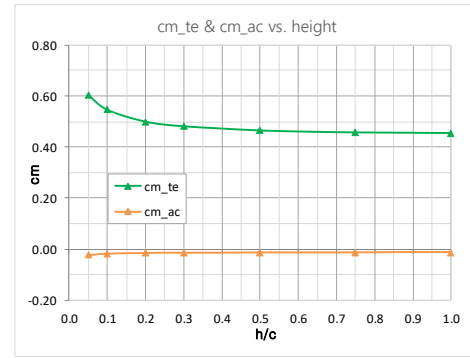
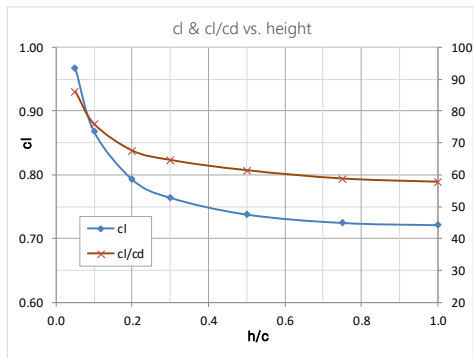
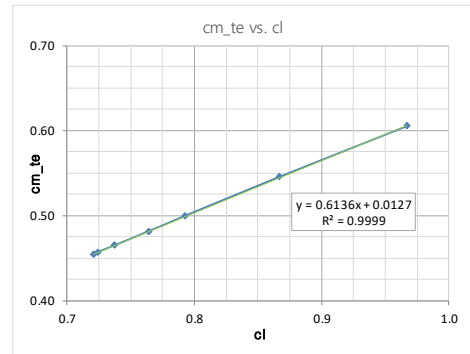


NACA 4412

alpha = 3 deg
x_ac = 0.65 from te

h/c	cl	cd	cm	cl/cd	cm_ac	
0.05	0.9670	0.01124	0.6055	86.0	-0.0231	1.492
0.1	0.8672	0.01145	0.5456	75.7	-0.0181	1.313
0.2	0.7925	0.01175	0.4993	67.4	-0.0158	1.169
0.3	0.7638	0.01185	0.4811	64.5	-0.0154	1.118
0.5	0.7376	0.01204	0.4650	61.3	-0.0144	1.062
0.75	0.7243	0.01234	0.4570	58.7	-0.0138	1.018
1.0	0.7209	0.01250	0.4550	57.7	-0.0136	-

mean = -0.0163
st. dev = 0.0033
pct. = 0.205

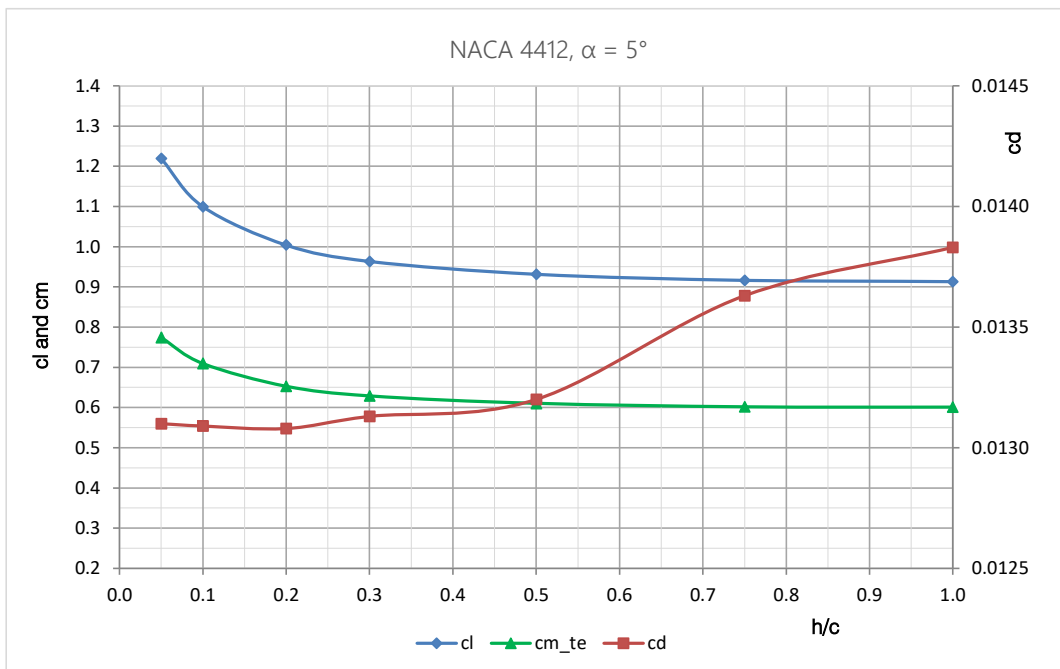
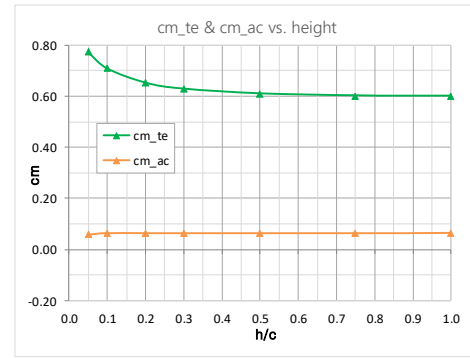
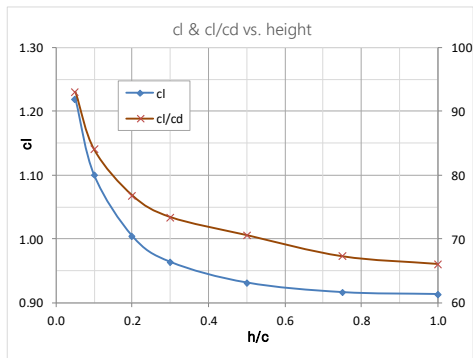
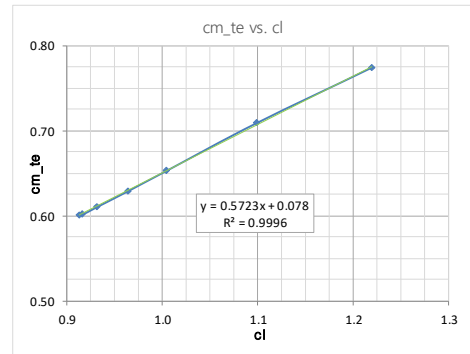


NACA 4412

alpha = 5 deg
x_ac = 0.587 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	1.219	0.01310	0.7740	93.1	0.0584	1.410
0.1	1.099	0.01309	0.7094	84.0	0.0643	1.272
0.2	1.004	0.01308	0.6530	76.8	0.0637	1.163
0.3	0.9633	0.01313	0.6289	73.4	0.0634	1.111
0.5	0.9310	0.01320	0.6101	70.5	0.0636	1.068
0.75	0.9162	0.01363	0.6018	67.2	0.0640	1.018
1.0	0.9130	0.01383	0.6005	66.0	0.0646	-

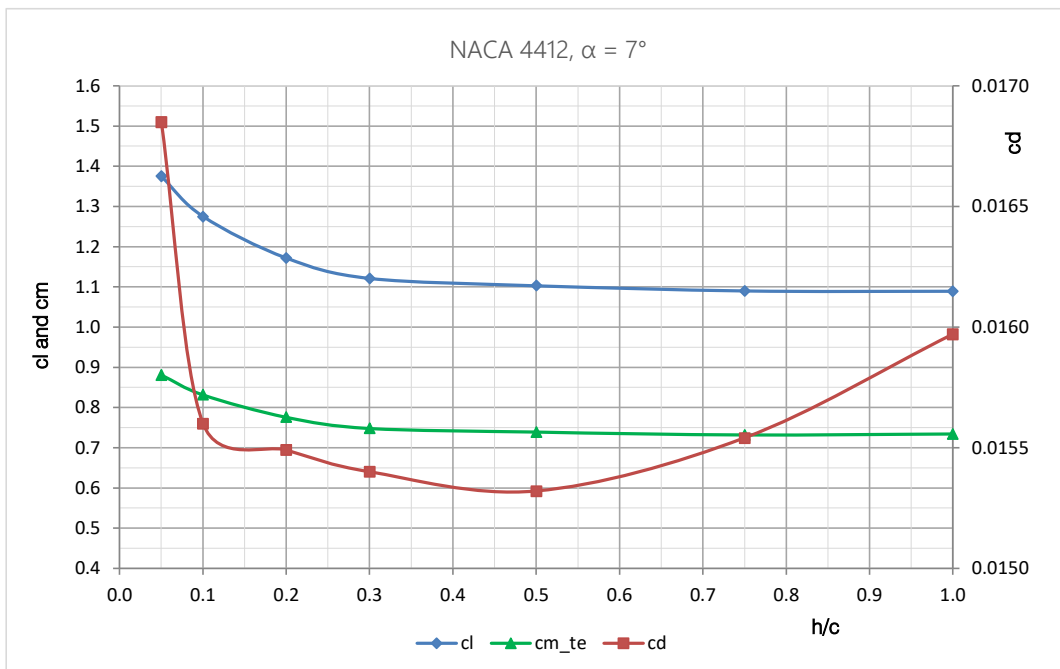
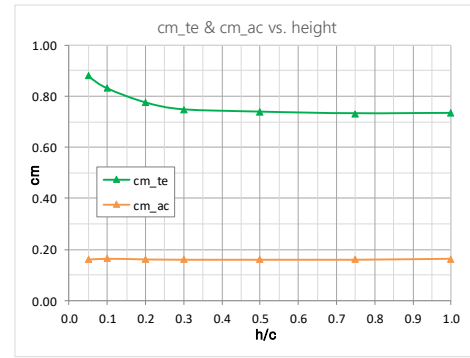
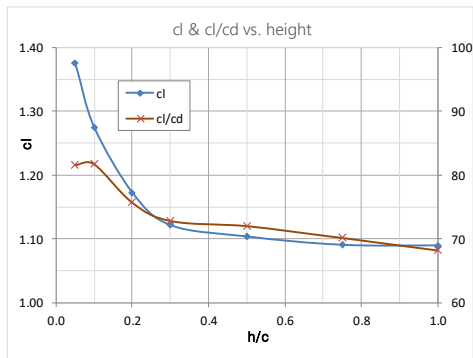
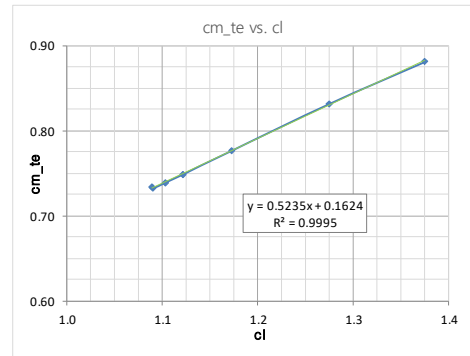
mean = 0.0631
st. dev = 0.0021
pct. = 0.033



NACA 4412

alpha = 7 deg
x_ac = 0.524 from te

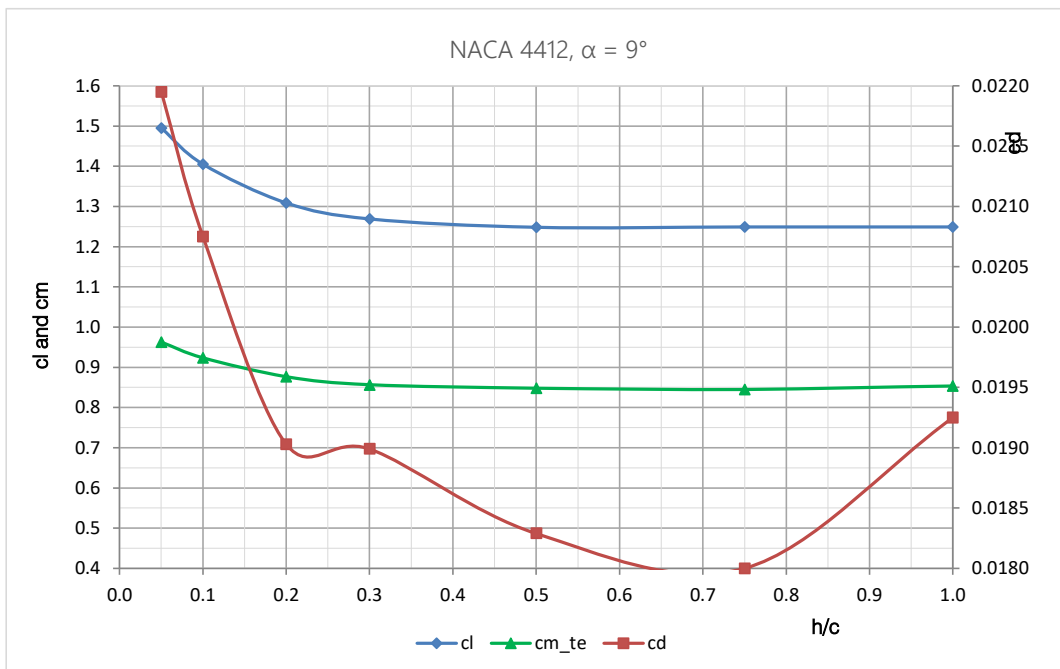
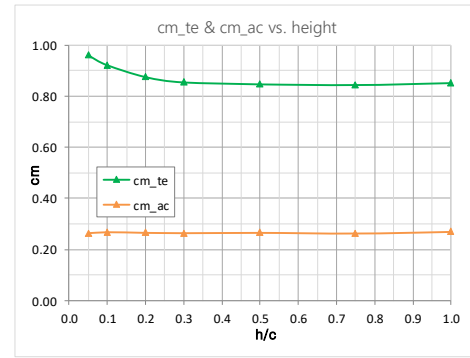
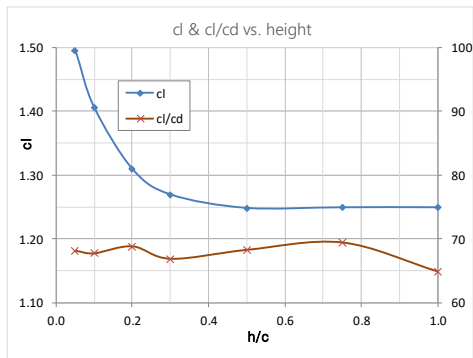
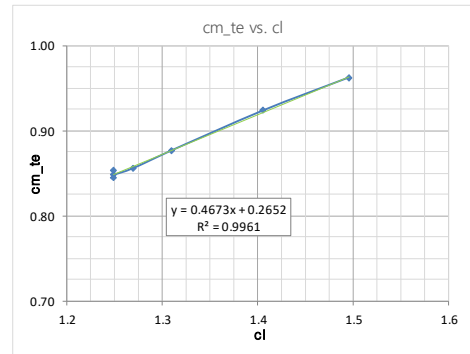
h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	1.375	0.01685	0.8810	81.6	0.1605	1.197
0.1	1.275	0.01560	0.8317	81.7	0.1636	1.199
0.2	1.172	0.01549	0.7762	75.7	0.1621	1.110
0.3	1.121	0.01540	0.7483	72.8	0.1609	1.067
0.5	1.103	0.01532	0.7389	72.0	0.1609	1.056
0.75	1.090	0.01554	0.7321	70.1	0.1609	1.029
1.0	1.089	0.01597	0.7341	68.2	0.1635	-
					mean =	0.1618
					st. dev =	0.0013
					pct. =	0.008



NACA 4412

alpha = 9 deg
x_ac = 0.467 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	1.495	0.02195	0.9626	68.1	0.2644	1.050
0.1	1.405	0.02075	0.9237	67.7	0.2676	1.044
0.2	1.309	0.01903	0.8768	68.8	0.2655	1.060
0.3	1.269	0.01899	0.8562	66.8	0.2636	1.030
0.5	1.248	0.01829	0.8482	68.2	0.2654	1.052
0.75	1.249	0.01800	0.8450	69.4	0.2617	1.069
1.0	1.249	0.01925	0.8537	64.9	0.2704	-
					mean =	0.2655
					st. dev =	0.0028
					pct. =	0.011

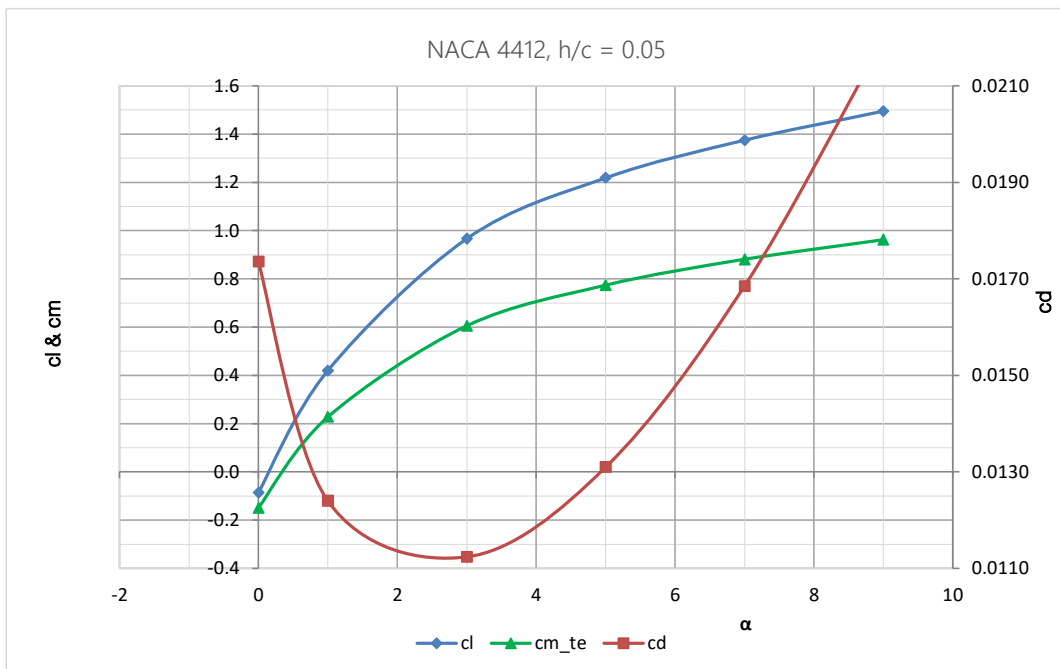
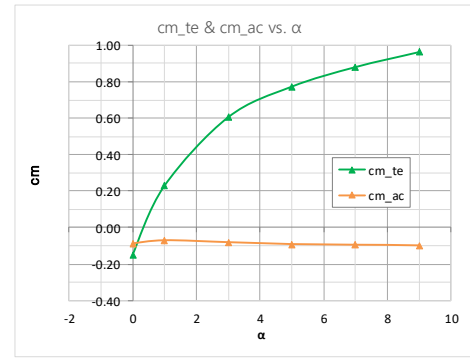
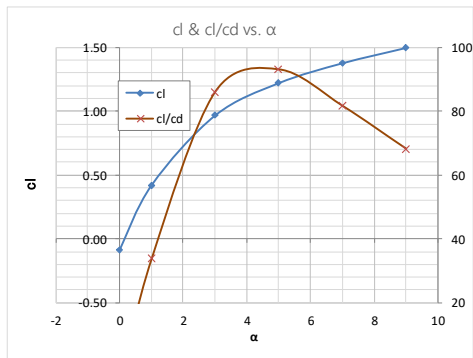
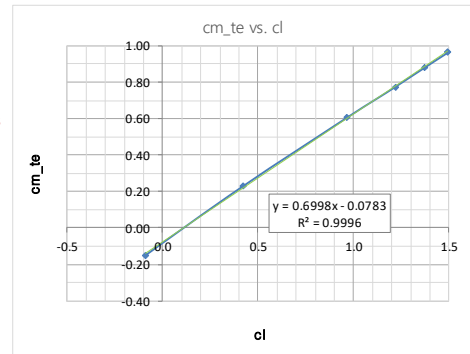


NACA 4412

h/c = 0.05
x_ac = 0.710 from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2						
0	-0.0864	0.01736	-0.1492	-5.0	-0.0879	-0.073
1	0.4198	0.01240	0.2279	33.9	-0.0702	0.497
3	0.9670	0.01124	0.6055	86.0	-0.0811	1.263
5	1.219	0.01310	0.7740	93.1	-0.0915	1.366
7	1.375	0.01685	0.8810	81.6	-0.0952	1.198
9	1.495	0.02195	0.9626	68.1	-0.0989	-

mean = -0.0874
st. dev = 0.0105
pct. = 0.120

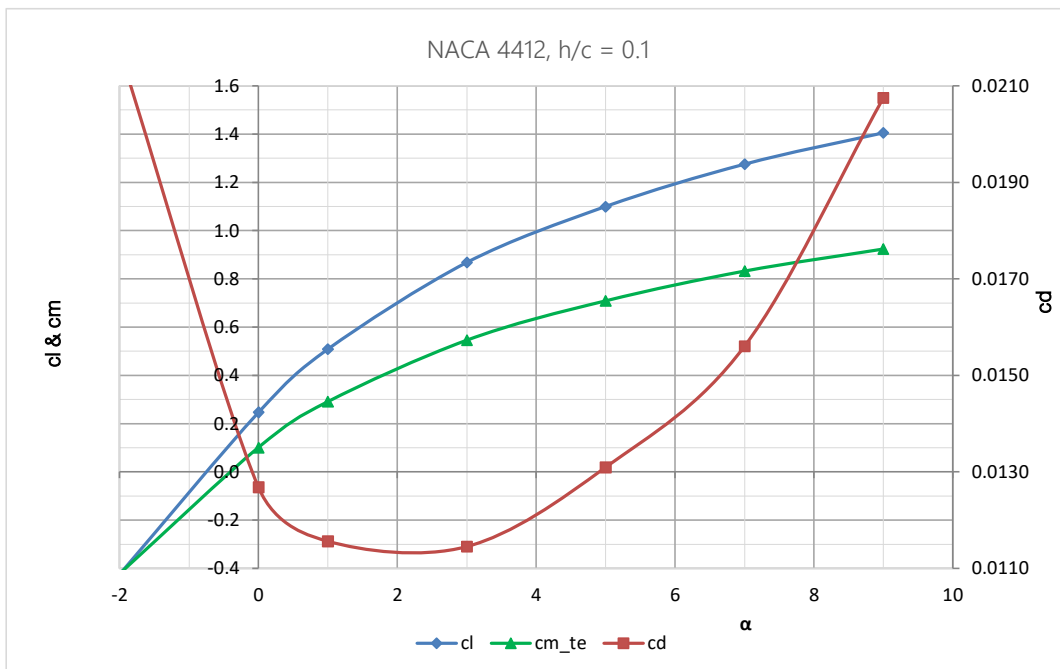
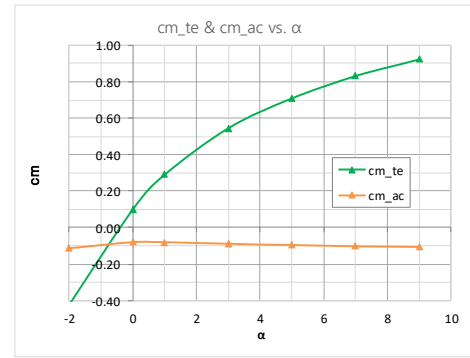
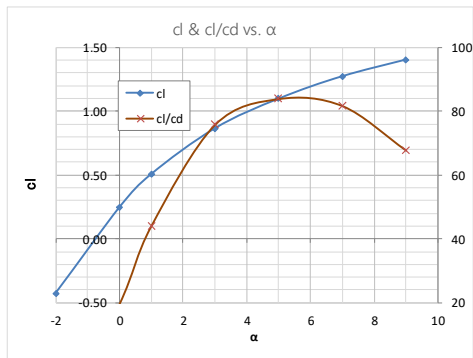
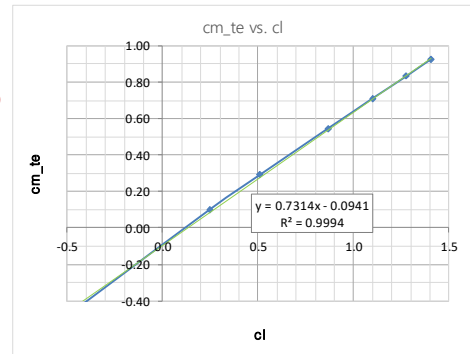


NACA 4412

h/c = 0.1
x_ac = 0.731 from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.4255	0.02174	-0.4225	-19.6	-0.1115	-0.289
0	0.2461	0.01268	0.1007	19.4	-0.0792	0.287
1	0.5082	0.01156	0.2913	44.0	-0.0802	0.649
3	0.8672	0.01145	0.5456	75.7	-0.0883	1.119
5	1.099	0.01309	0.7094	84.0	-0.0940	1.240
7	1.275	0.01560	0.8317	81.7	-0.1003	1.207
9	1.405	0.02075	0.9237	67.7	-0.1034	-

mean = -0.0938
st. dev = 0.0121
pct. = 0.129

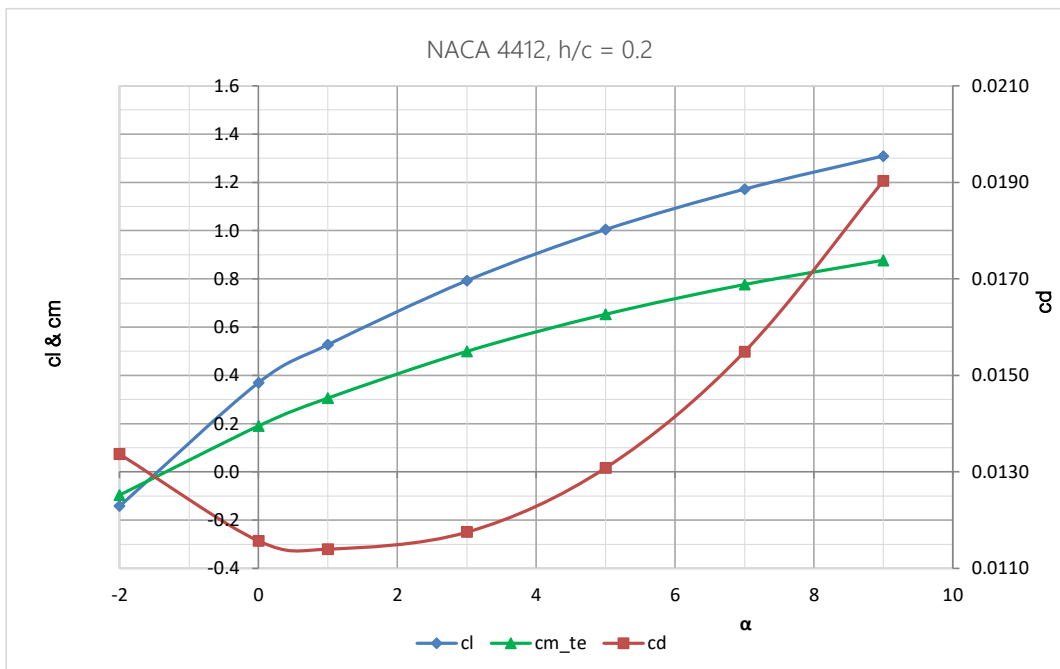
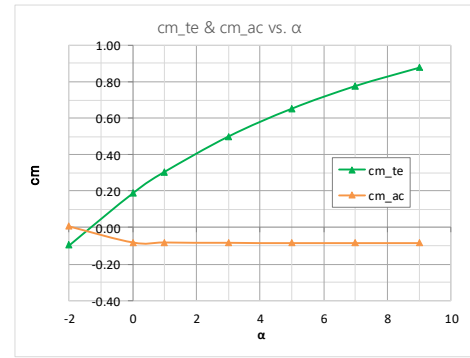
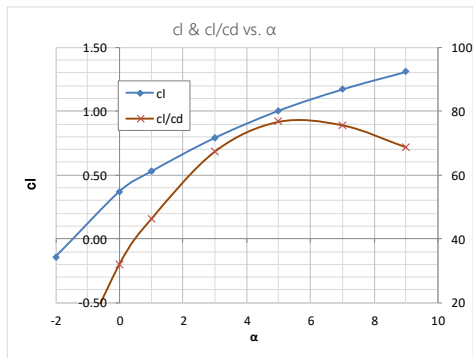
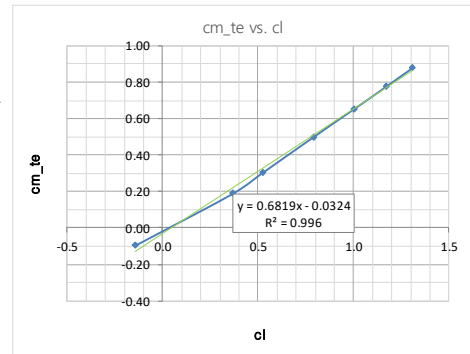


NACA 4412

h/c = 0.2
x_ac = 0.735 from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.1420	0.01337	-0.0966	-10.6	0.0078	-0.154
0	0.3695	0.01157	0.1898	31.9	-0.0818	0.464
1	0.5271	0.01140	0.3058	46.2	-0.0816	0.672
3	0.7925	0.01175	0.4993	67.4	-0.0832	0.981
5	1.004	0.01308	0.6530	76.8	-0.0849	1.116
7	1.172	0.01549	0.7762	75.7	-0.0852	1.100
9	1.309	0.01903	0.8768	68.8	-0.0853	-

mean = -0.0706
st. dev = 0.0346
pct. = 0.490

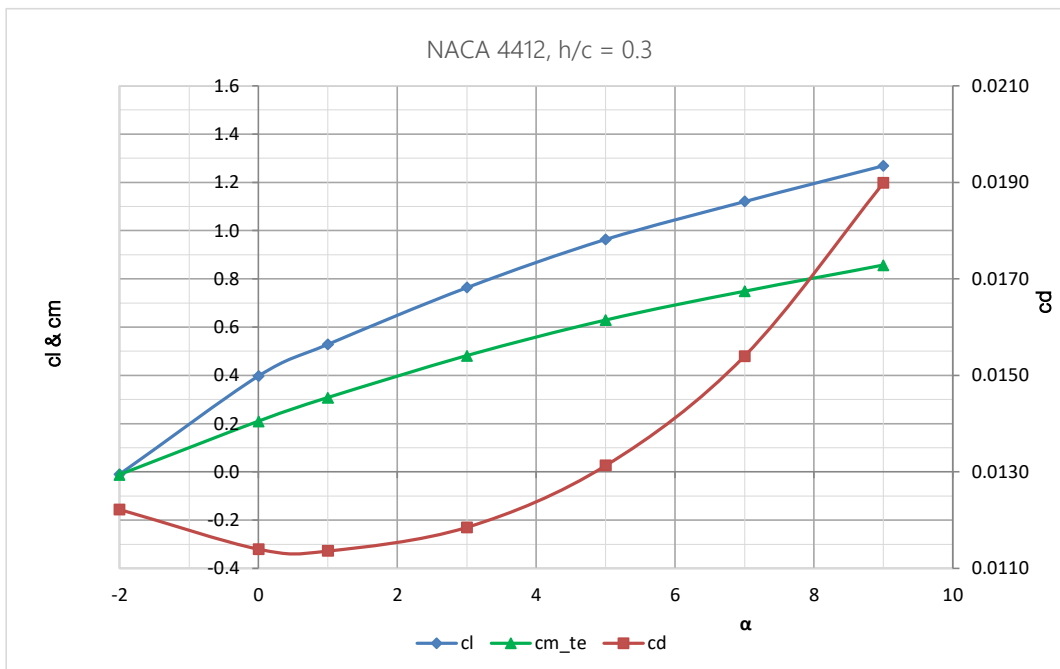
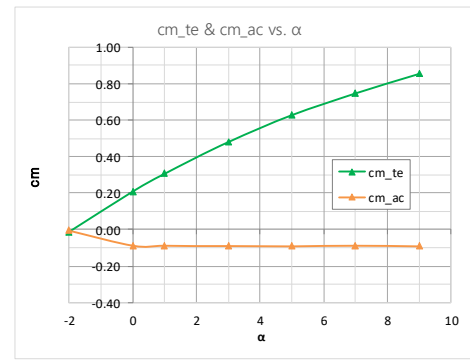
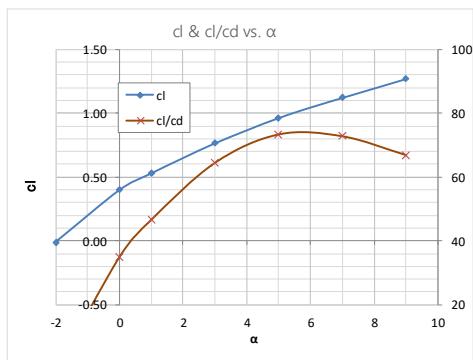
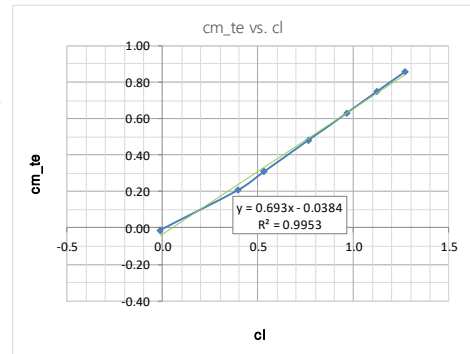


NACA 4412

h/c = 0.3
x_ac = 0.745 from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.0105	0.01222	-0.0121	-0.9	-0.0043	-0.013
0	0.3966	0.01140	0.2092	34.8	-0.0863	0.521
1	0.5290	0.01136	0.3074	46.6	-0.0867	0.697
3	0.7638	0.01185	0.4811	64.5	-0.0879	0.965
5	0.963	0.01313	0.6289	73.4	-0.0888	1.098
7	1.121	0.01540	0.7483	72.8	-0.0868	1.089
9	1.269	0.01899	0.8562	66.8	-0.0892	-

mean = -0.0757
st. dev = 0.0315
pct. = 0.416

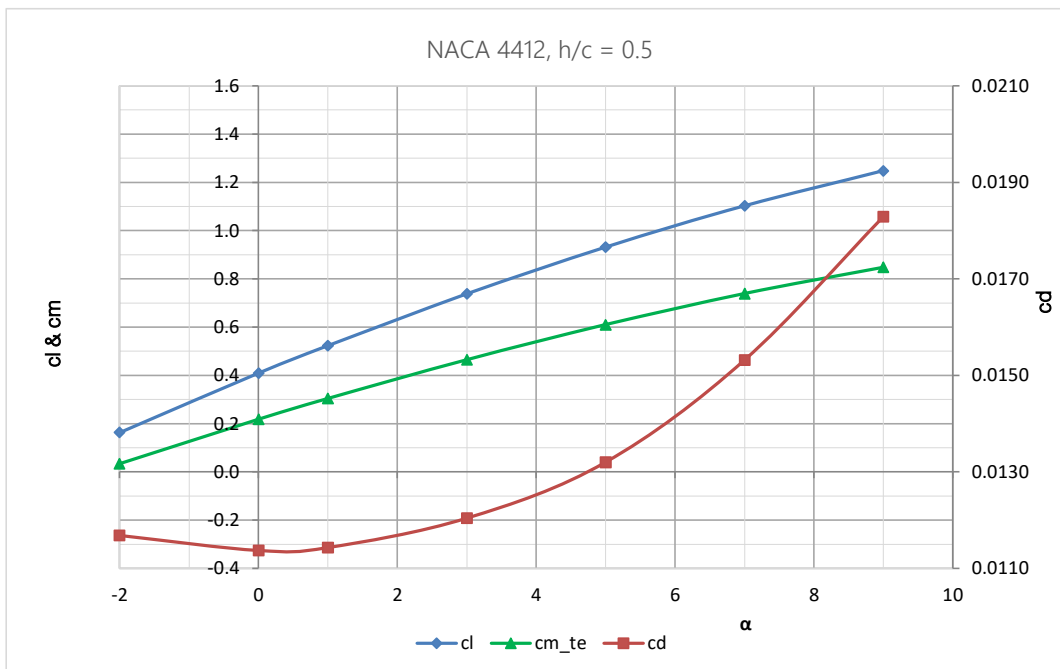
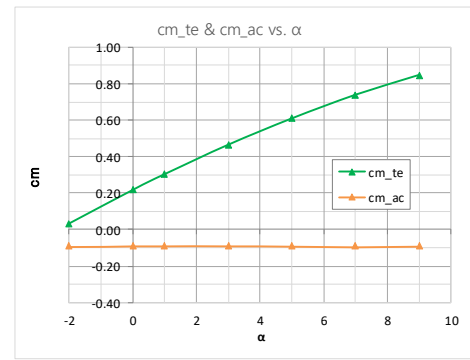
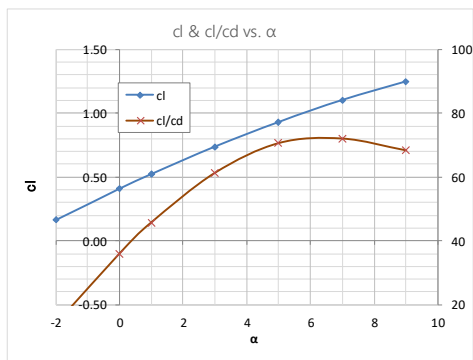
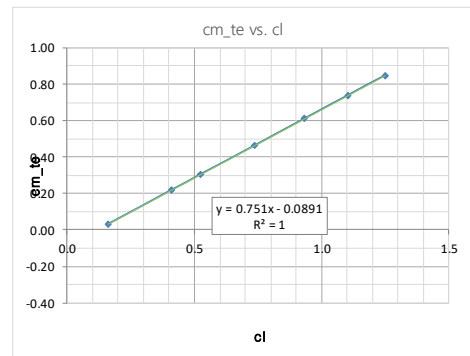


NACA 4412

h/c = 0.5
x_ac = 0.751 from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	0.1632	0.01168	0.0332	14.0	-0.0894	0.205
0	0.4089	0.01137	0.2181	36.0	-0.0890	0.527
1	0.5231	0.01143	0.3040	45.8	-0.0888	0.671
3	0.7376	0.01204	0.4650	61.3	-0.0889	0.898
5	0.931	0.01320	0.6101	70.5	-0.0891	1.034
7	1.103	0.01532	0.7389	72.0	-0.0895	1.055
9	1.248	0.01829	0.8482	68.2	-0.0890	-

mean = -0.0891
st. dev = 0.0002
pct. = 0.003

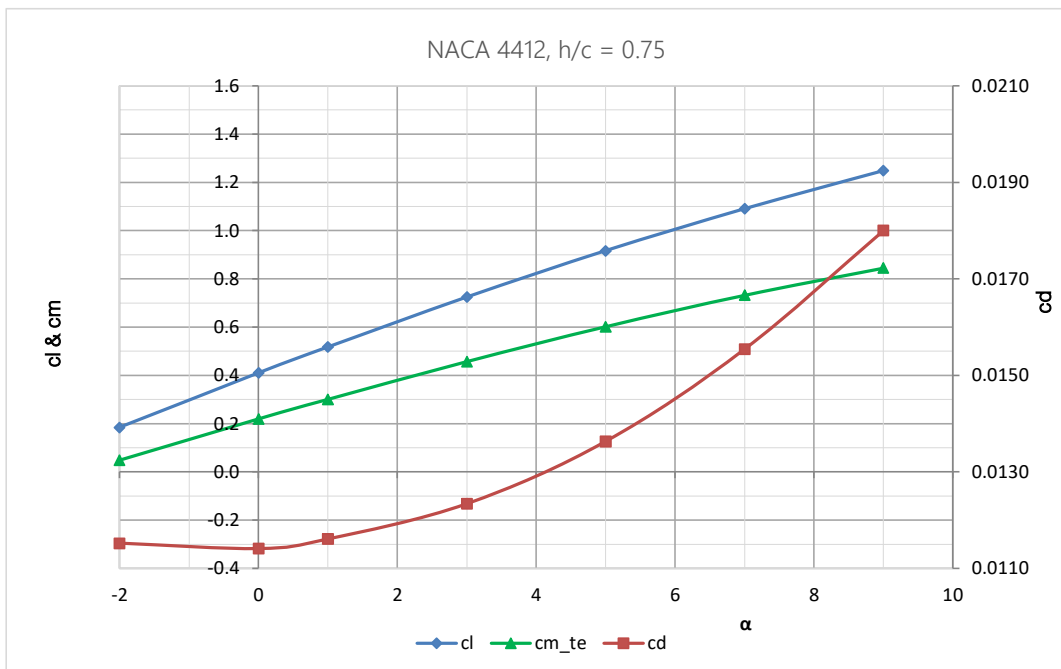
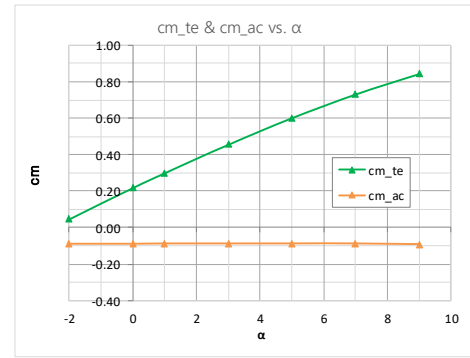
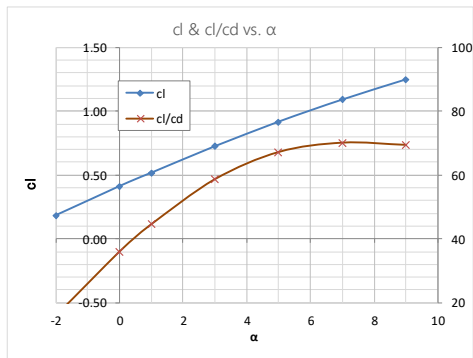
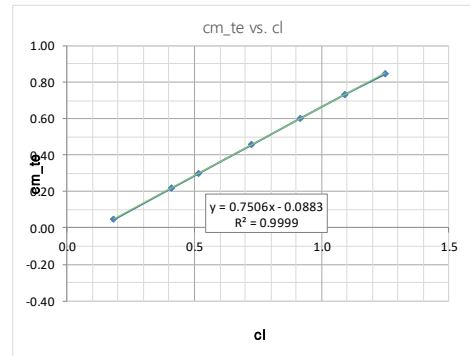


NACA 4412

h/c = 0.75
x_ac = 0.751 from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	0.1838	0.01152	0.0479	16.0	-0.0901	0.230
0	0.4103	0.01141	0.2193	36.0	-0.0888	0.518
1	0.5174	0.01161	0.3006	44.6	-0.0880	0.642
3	0.7243	0.01234	0.4570	58.7	-0.0869	0.846
5	0.916	0.01363	0.6018	67.2	-0.0863	0.969
7	1.090	0.01554	0.7321	70.1	-0.0865	1.011
9	1.249	0.01800	0.8450	69.4	-0.0930	-

mean = -0.0885
st. dev = 0.0024
pct. = 0.027

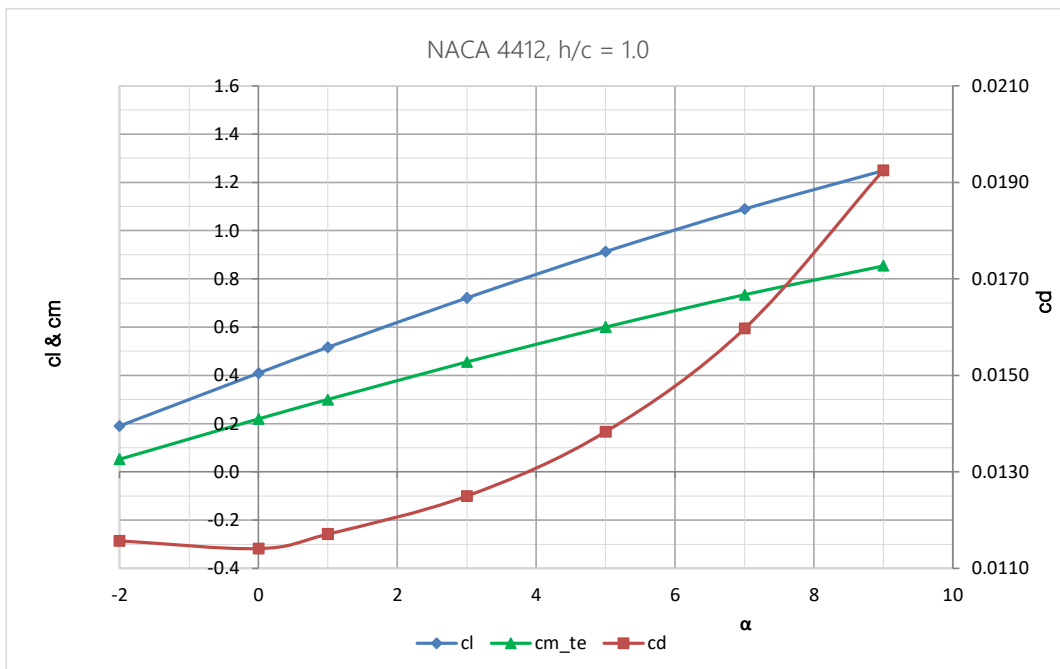
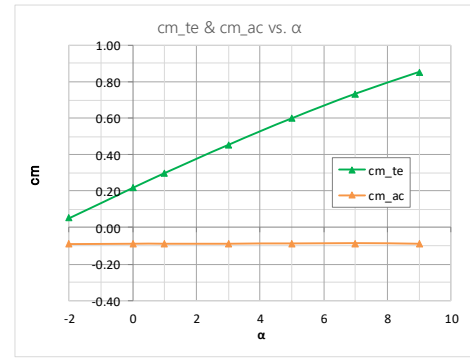
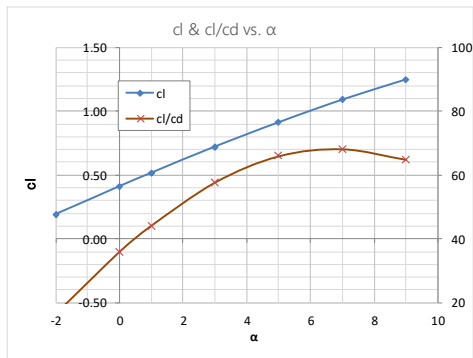
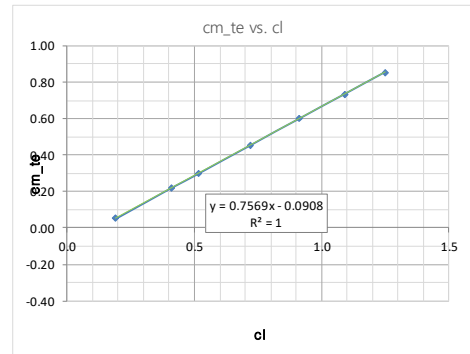


NACA 4412

h/c = 1
x_ac = 0.755 from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	0.1902	0.01157	0.0525	16.4	-0.0911	0.253
0	0.4089	0.01141	0.2193	35.8	-0.0894	0.552
1	0.5160	0.01171	0.2997	44.1	-0.0899	0.679
3	0.7209	0.01250	0.4550	57.7	-0.0893	0.889
5	0.913	0.01383	0.6005	66.0	-0.0888	1.017
7	1.089	0.01597	0.7341	68.2	-0.0881	1.051
9	1.249	0.01925	0.8537	64.9	-0.0893	-

mean = -0.0894
st. dev = 0.0009
pct. = 0.010

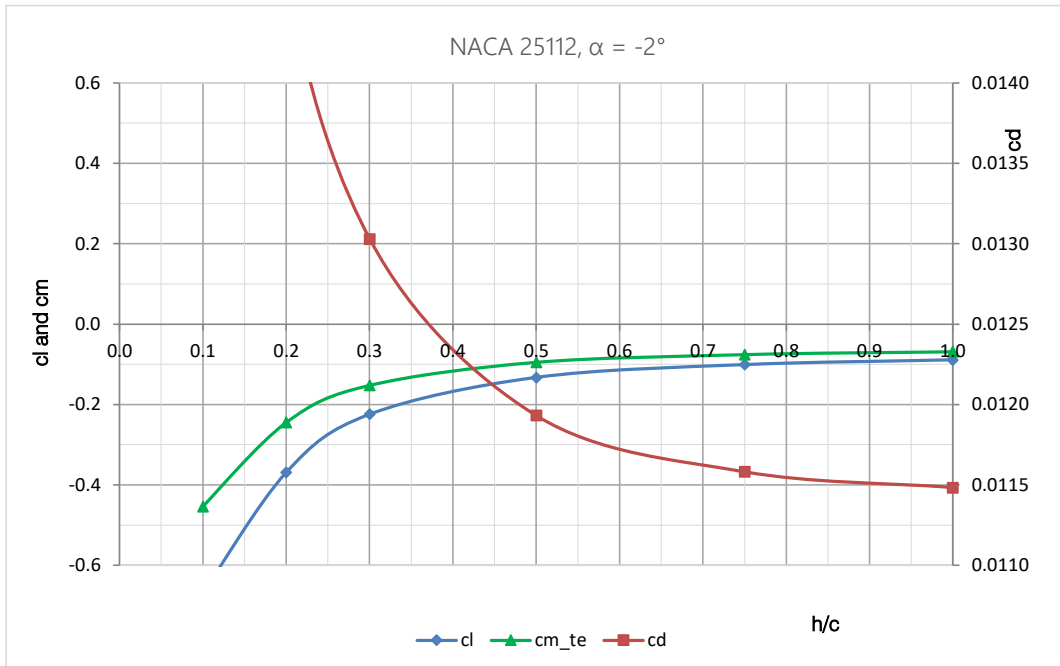
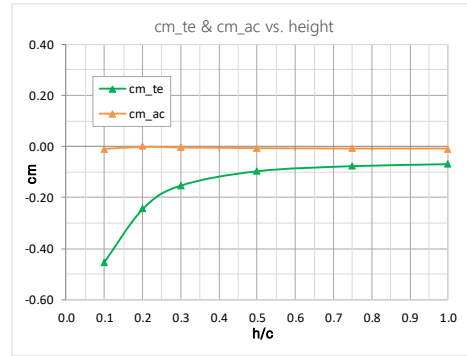
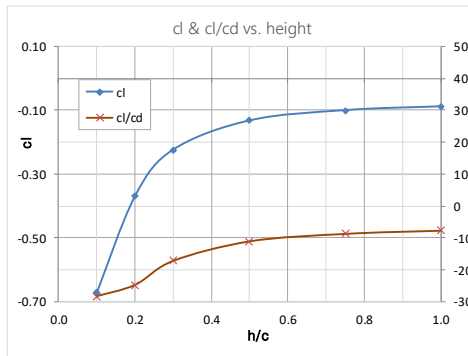
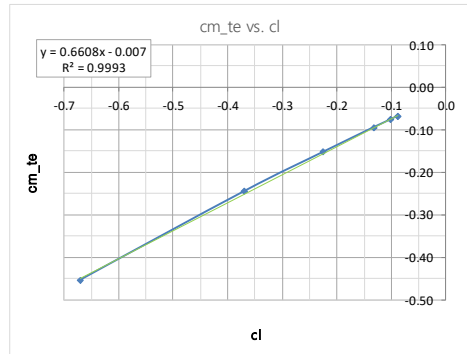


8.8 Appendix – Detailed Results NACA 25112

NACA 25112

alpha = -2 deg
x_ac = 0.660 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05						
0.1	-0.6703	0.02358	-0.4535	-28.4	-0.0111	3.663
0.2	-0.3690	0.01486	-0.2446	-24.8	-0.0011	3.199
0.3	-0.2245	0.01303	-0.1523	-17.2	-0.0042	2.220
0.5	-0.1329	0.01193	-0.0954	-11.1	-0.0077	1.435
0.75	-0.1010	0.01158	-0.0759	-8.7	-0.0093	1.123
1.0	-0.0891	0.01148	-0.0687	-7.8	-0.0099	-
					mean =	-0.0072
					st. dev =	0.0038
					pct. =	0.533

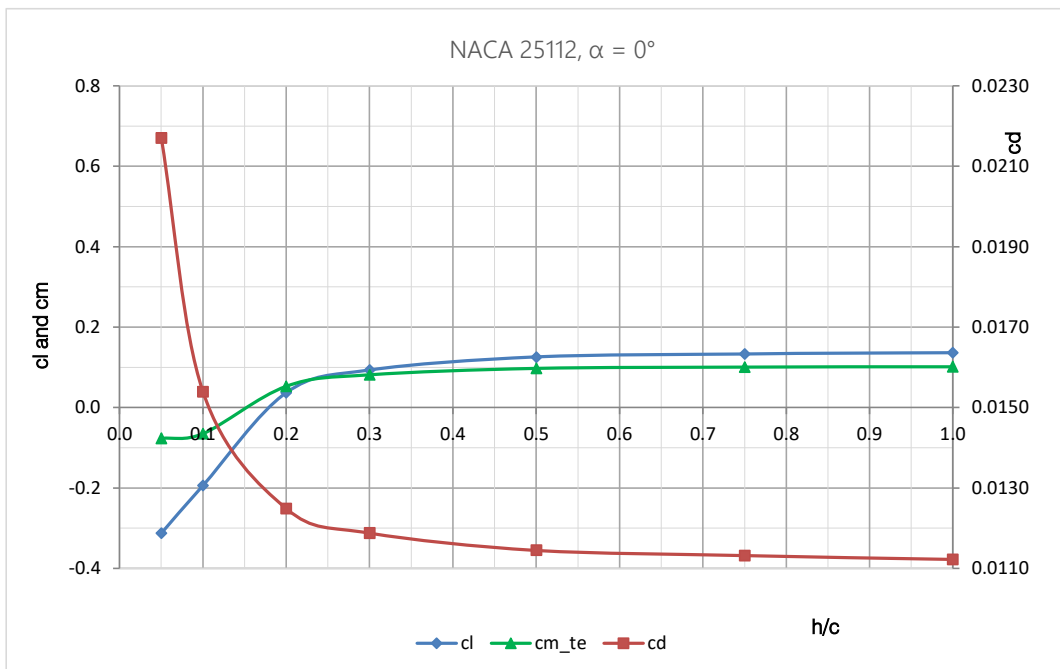
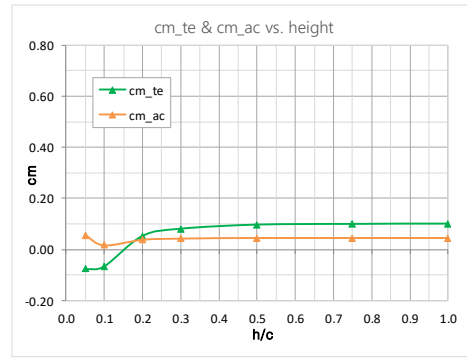
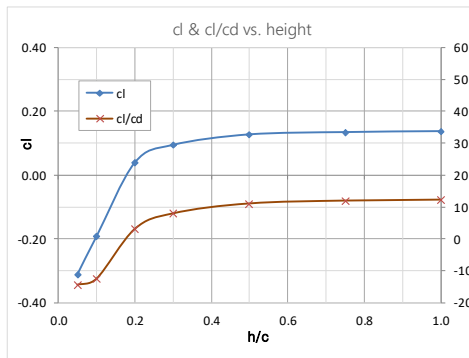
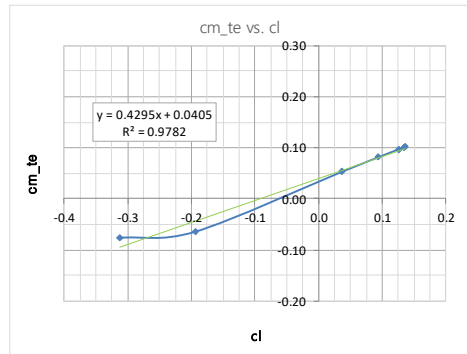


NACA 25112

alpha = 0 deg
x_ac = 0.423 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	-0.3127	0.02170	-0.0769	-14.4	0.0554	-1.187
0.1	-0.1940	0.01539	-0.0650	-12.6	0.0170	-1.038
0.2	0.0369	0.01249	0.0529	3.0	0.0373	0.243
0.3	0.0935	0.01188	0.0815	7.9	0.0419	0.648
0.5	0.1257	0.01145	0.0972	11.0	0.0440	0.904
0.75	0.1335	0.01132	0.1004	11.8	0.0439	0.972
1.0	0.1362	0.01122	0.1016	12.1	0.0440	-

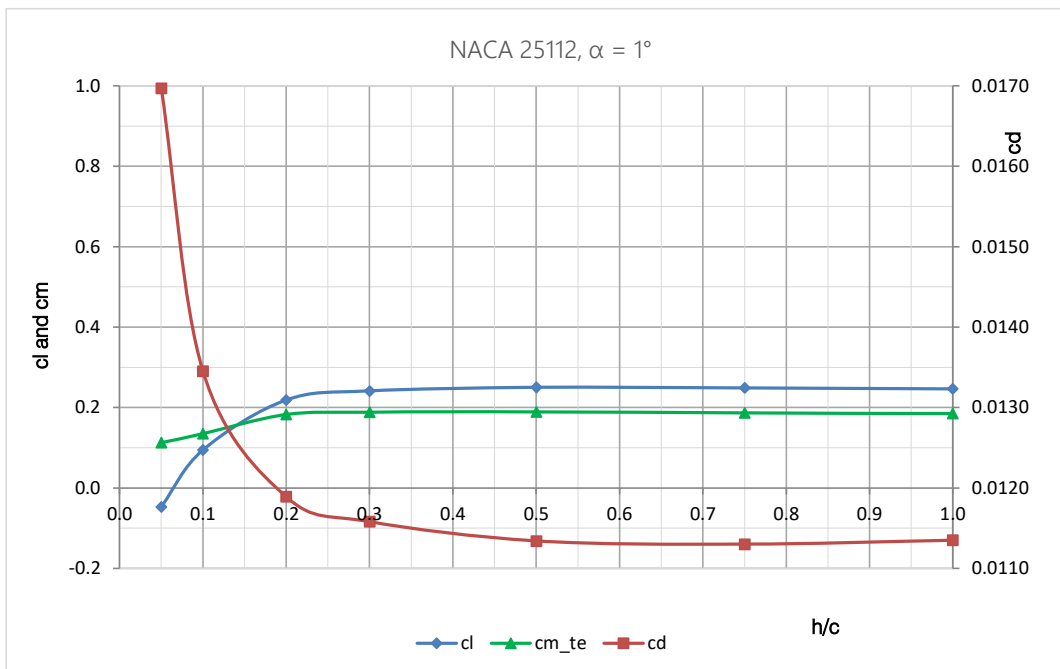
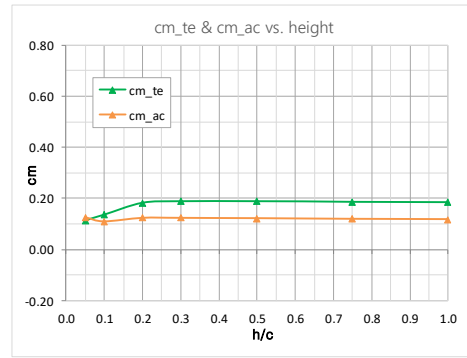
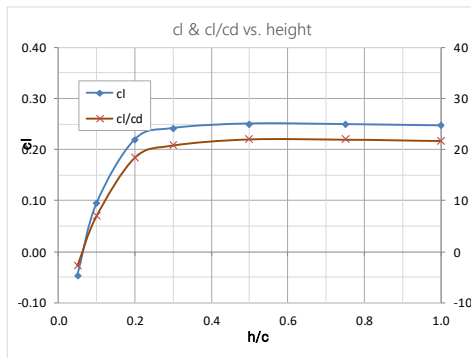
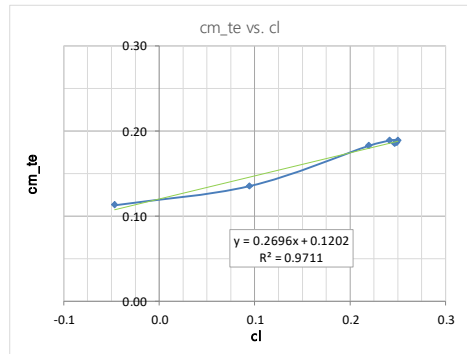
mean = 0.0405
st. dev = 0.0117
pct. = 0.289



NACA 25112

alpha = 1 deg
x_ac = 0.270 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	-0.0470	0.01697	0.1127	-2.8	0.1254	-0.128
0.1	0.0943	0.01345	0.1349	7.0	0.1094	0.323
0.2	0.2186	0.01189	0.1822	18.4	0.1232	0.847
0.3	0.2410	0.01158	0.1885	20.8	0.1234	0.959
0.5	0.2500	0.01134	0.1892	22.0	0.1217	1.016
0.75	0.2486	0.01130	0.1866	22.0	0.1195	1.014
1.0	0.2463	0.01135	0.1846	21.7	0.1181	-
					mean =	0.1201
					st. dev =	0.0053
					pct. =	0.044

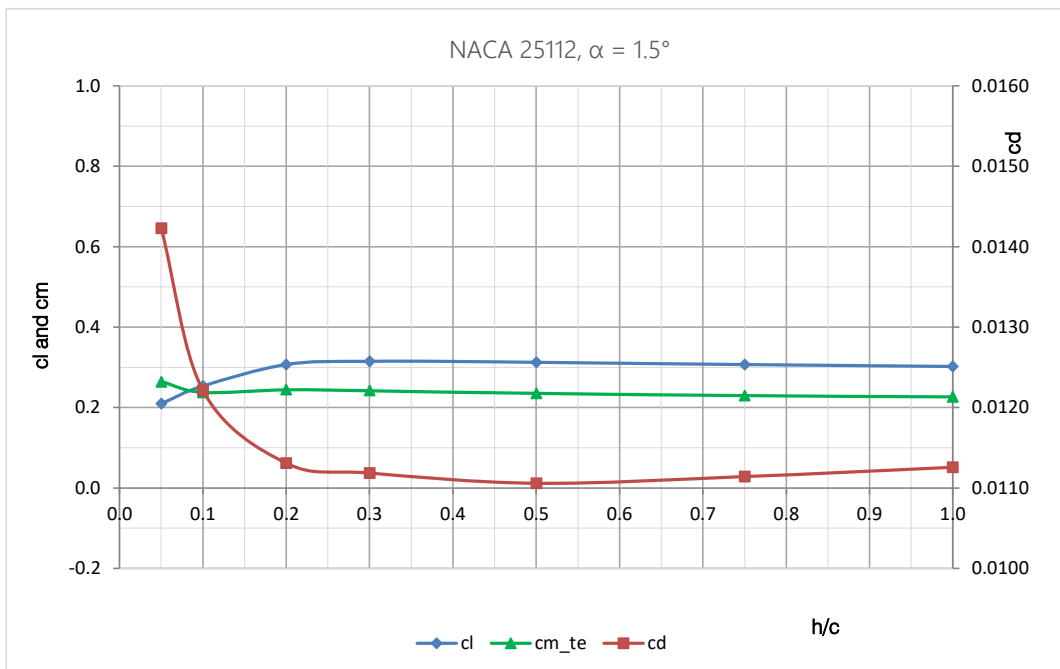
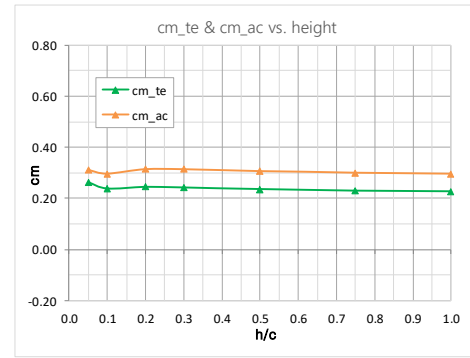
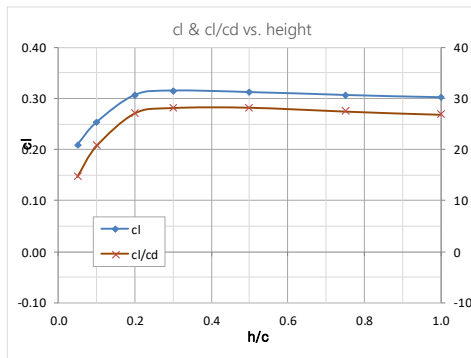
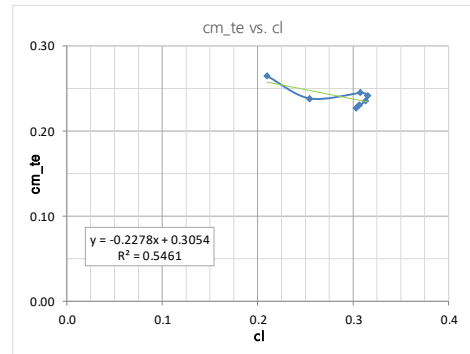


NACA 25112

alpha = 1.5 deg
x_ac = -0.228 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	0.2096	0.01423	0.26425	14.7	0.3120	0.548
0.1	0.2535	0.01221	0.2378	20.8	0.2956	0.773
0.2	0.3069	0.01131	0.2443	27.1	0.3143	1.010
0.3	0.3152	0.01119	0.2419	28.2	0.3137	1.049
0.5	0.3125	0.01106	0.2354	28.3	0.3066	1.052
0.75	0.3066	0.01114	0.2300	27.5	0.2999	1.024
1.0	0.3024	0.01126	0.2268	26.9	0.2958	-

mean = 0.3054
st. dev = 0.0083
pct. = 0.027

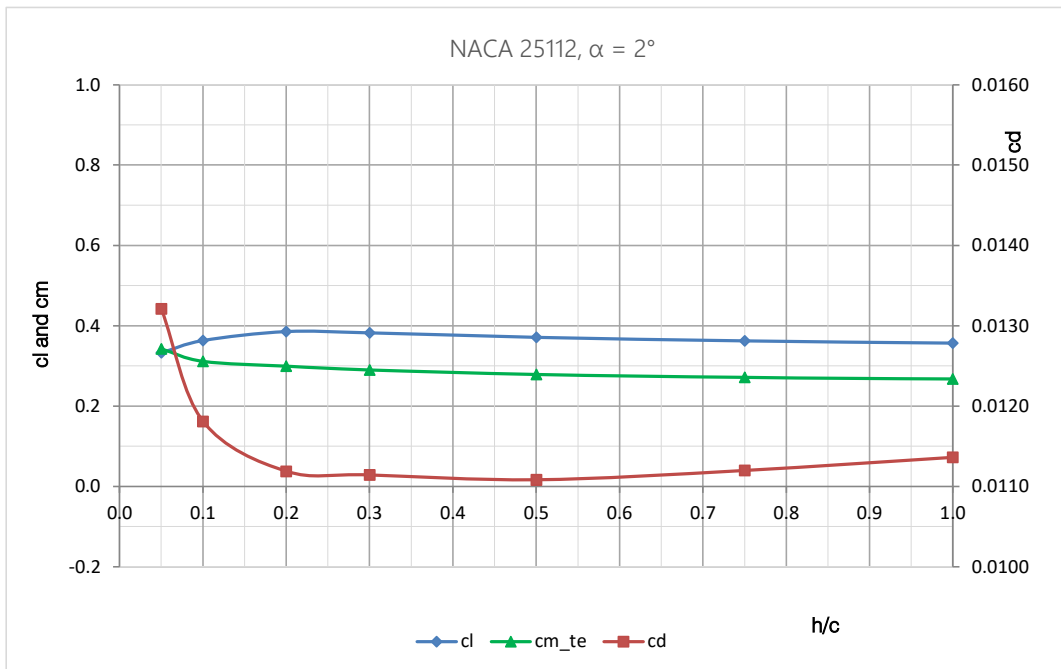
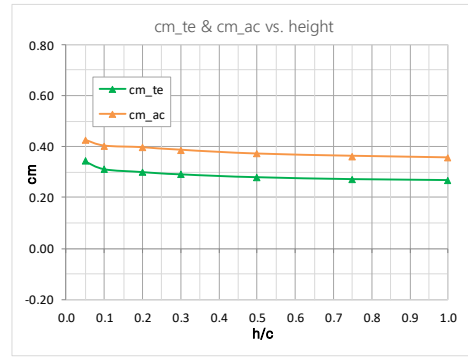
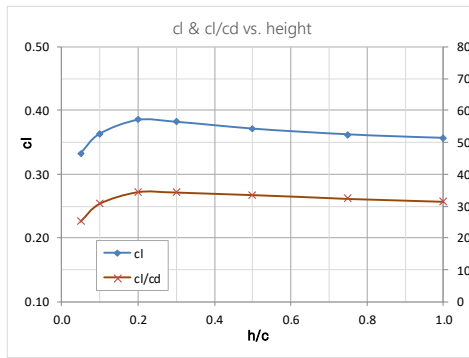
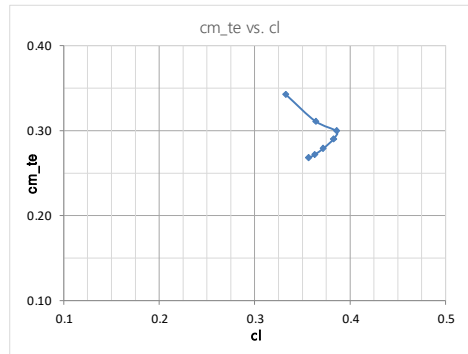


NACA 25112

alpha = 2 deg
x_ac = -0.250 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	0.3325	0.01321	0.3424	25.2	0.4255	0.802
0.1	0.3632	0.01181	0.3112	30.8	0.4020	0.980
0.2	0.3851	0.01119	0.2994	34.4	0.3957	1.097
0.3	0.3822	0.01114	0.2903	34.3	0.3858	1.093
0.5	0.3713	0.01108	0.2788	33.5	0.3717	1.068
0.75	0.3621	0.01120	0.2715	32.3	0.3621	1.031
1.0	0.3565	0.01136	0.2675	31.4	0.3566	-

mean = 0.3856
st. dev = 0.0243
pct. = 0.063

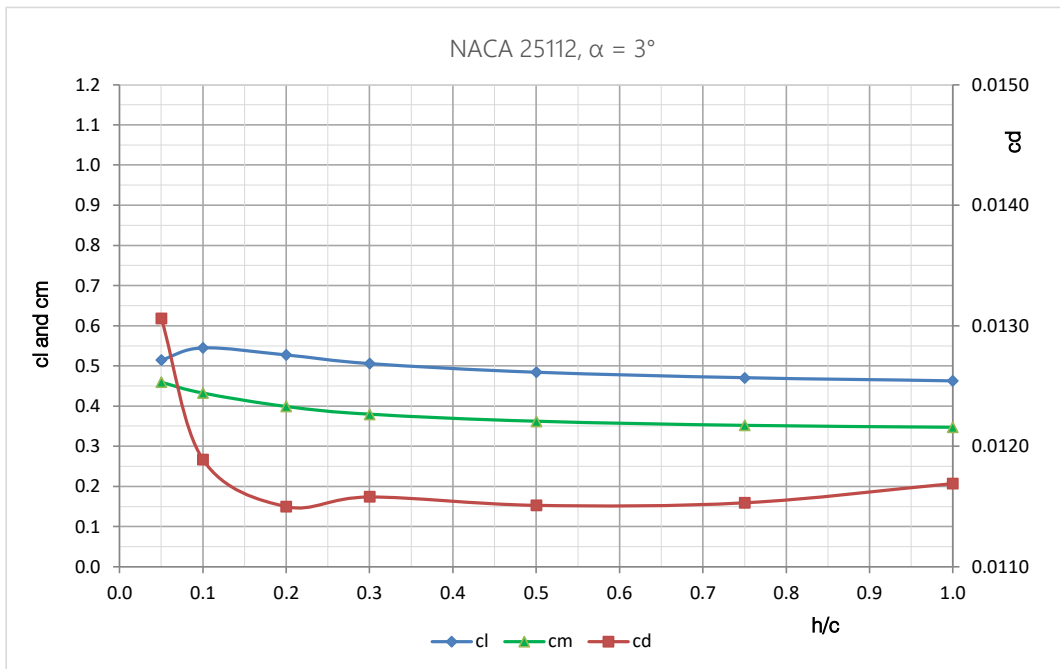
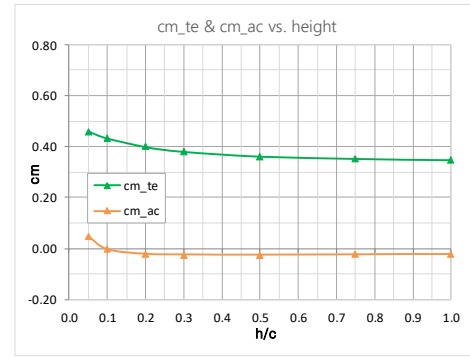
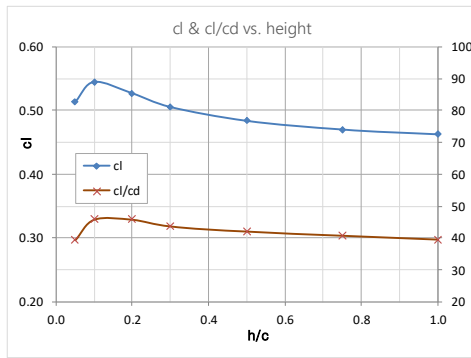
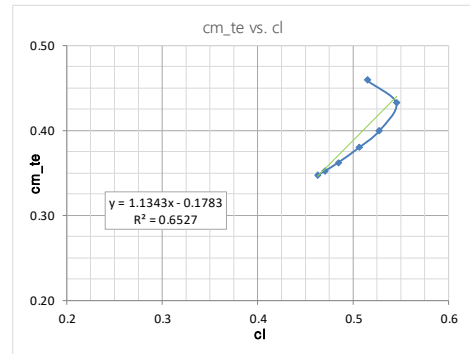


NACA 25112

alpha = 3 deg
x_ac = 0.8 from te

h/c	cl	cd	cm	cl/cd	cm_ac	
0.05	0.5143	0.01306	0.4595	39.4	0.0481	0.995
0.1	0.5450	0.01189	0.4324	45.8	-0.0036	1.158
0.2	0.5270	0.01150	0.3992	45.8	-0.0224	1.158
0.3	0.5058	0.01158	0.3797	43.7	-0.0249	1.103
0.5	0.4841	0.01151	0.3620	42.1	-0.0253	1.062
0.75	0.4703	0.01153	0.3523	40.8	-0.0239	1.030
1.0	0.4628	0.01169	0.3474	39.6	-0.0228	-

mean = -0.0107
st. dev = 0.0270
pct. = 2.523

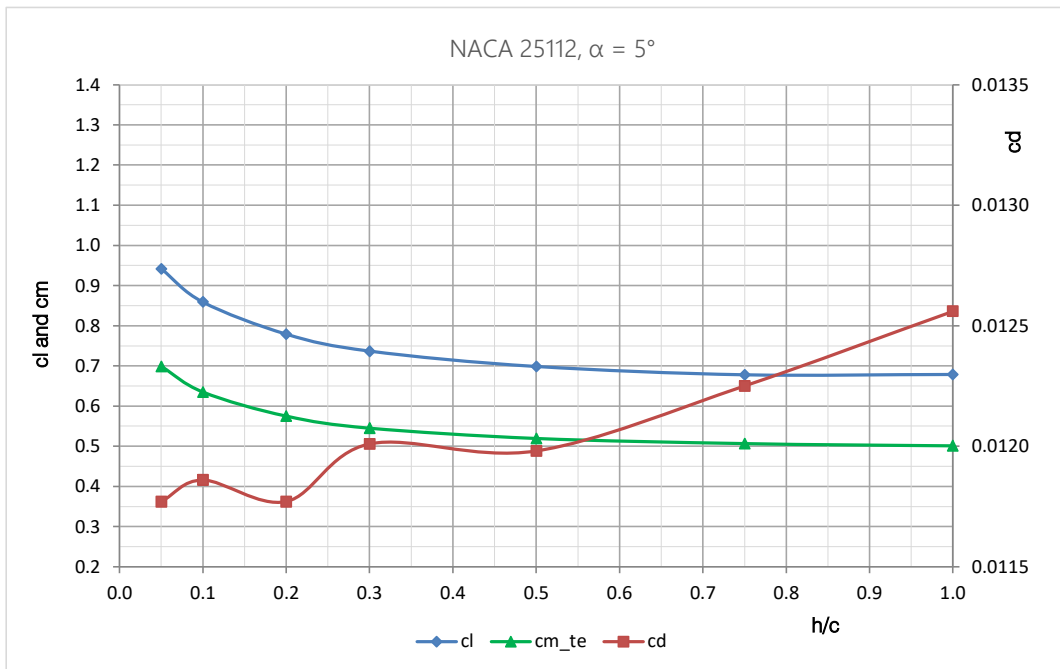
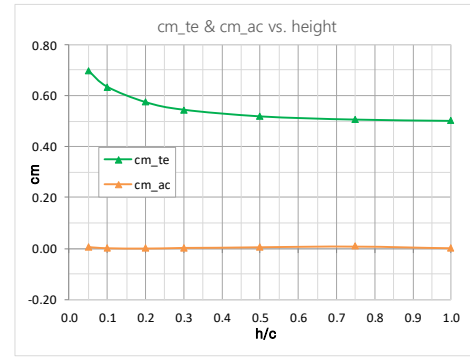
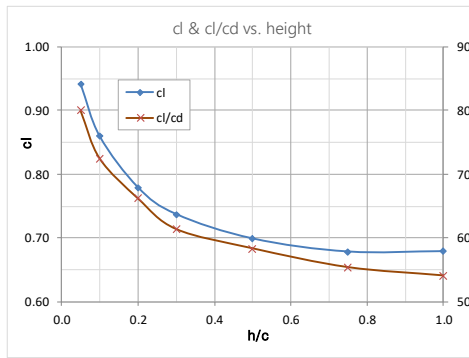
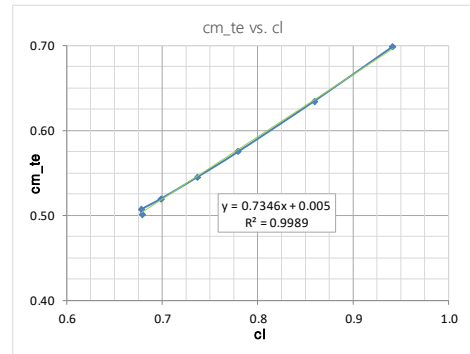


NACA 25112

alpha = 5 deg
x_ac = 0.735 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	0.9414	0.01177	0.6988	80.0	0.0069	1.480
0.1	0.8591	0.01186	0.6345	72.4	0.0031	1.341
0.2	0.7791	0.01177	0.5749	66.2	0.0023	1.225
0.3	0.7367	0.01201	0.5452	61.3	0.0037	1.135
0.5	0.6986	0.01198	0.5197	58.3	0.0062	1.079
0.75	0.6780	0.01225	0.5068	55.3	0.0085	1.024
1.0	0.6787	0.01256	0.5014	54.0	0.0026	-

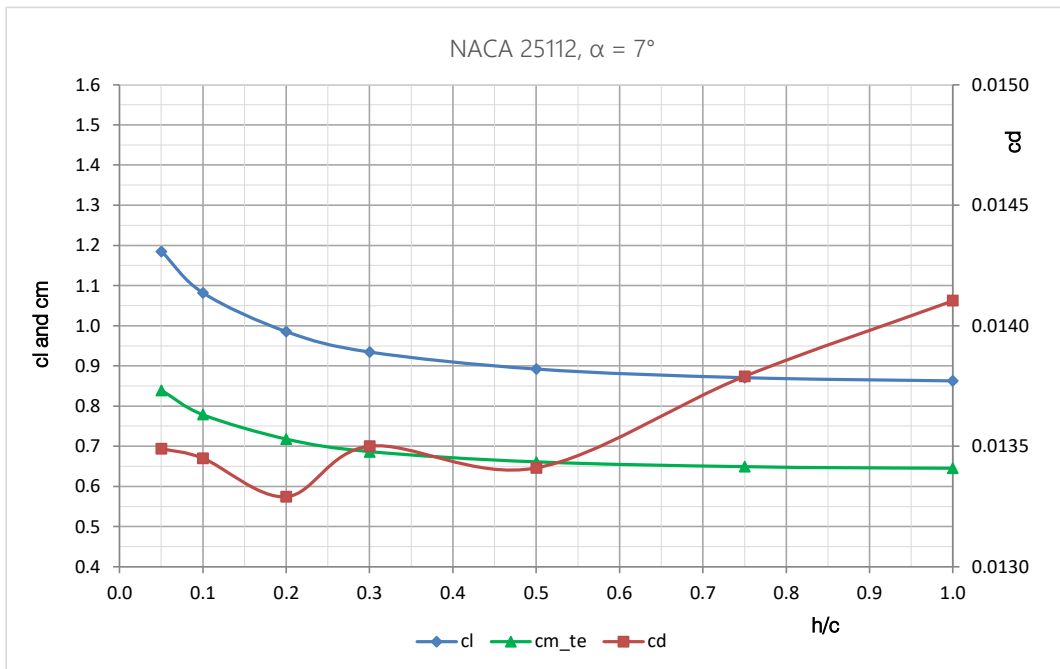
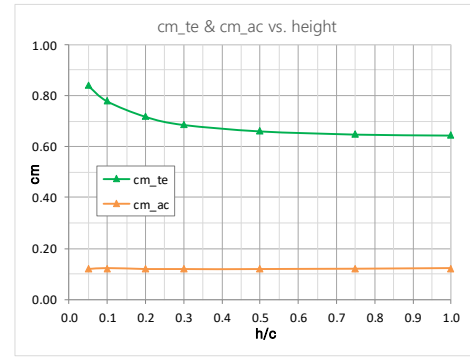
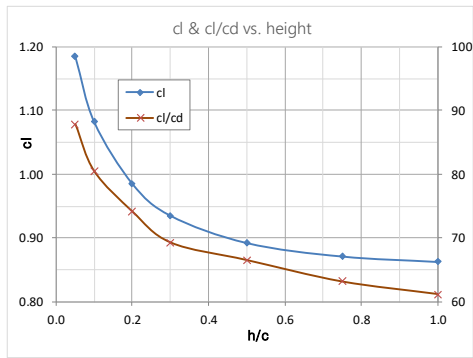
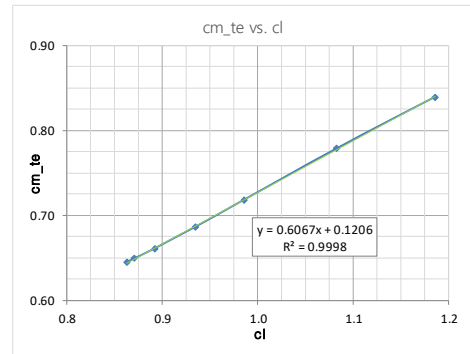
mean = 0.0047
st. dev = 0.0024
pct. = 0.513



NACA 25112

alpha = 7 deg
x_ac = 0.607 from te

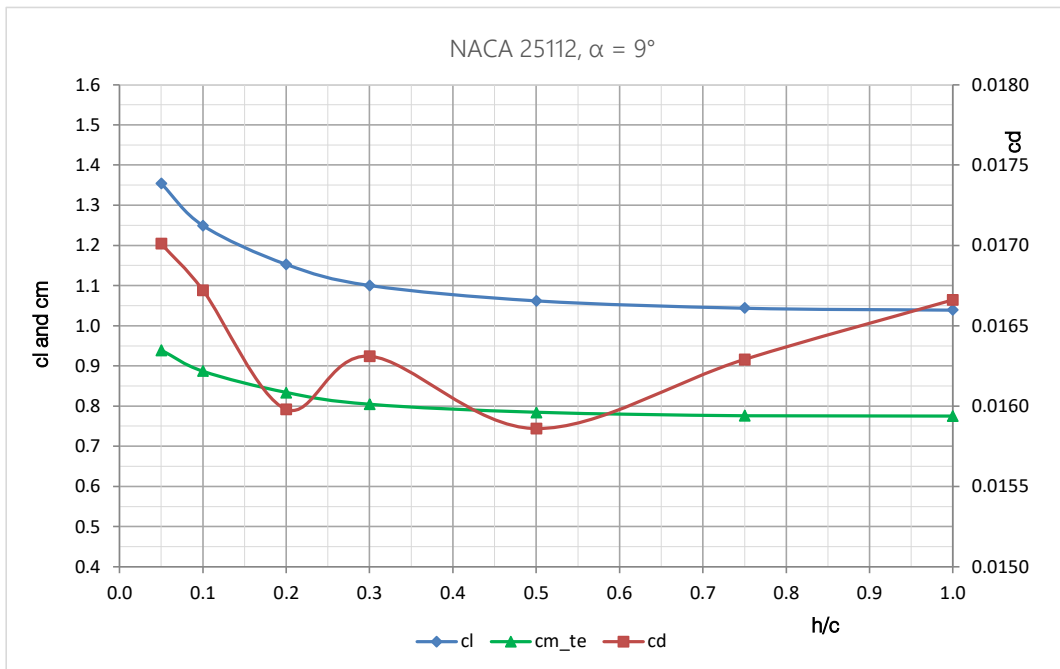
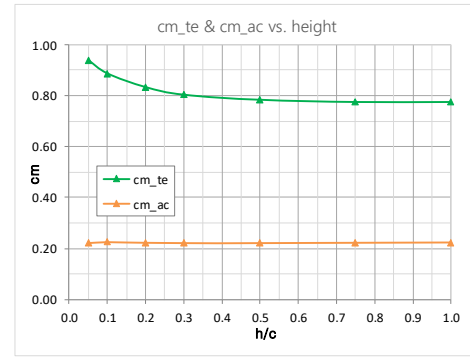
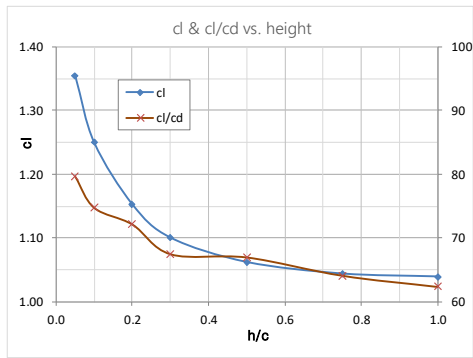
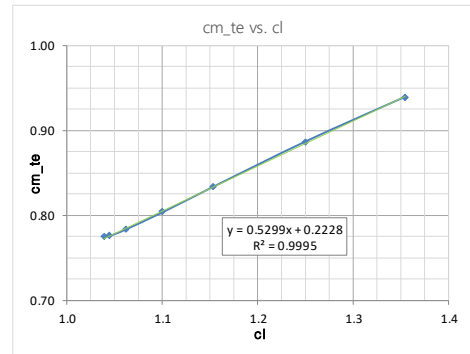
h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	1.185	0.01349	0.8391	87.8	0.1198	1.436
0.1	1.082	0.01345	0.7785	80.4	0.1217	1.315
0.2	0.985	0.01329	0.7180	74.1	0.1198	1.212
0.3	0.935	0.01350	0.6865	69.2	0.1191	1.132
0.5	0.892	0.01341	0.6609	66.5	0.1195	1.088
0.75	0.871	0.01379	0.6492	63.1	0.1206	1.033
1.0	0.863	0.01410	0.6453	61.2	0.1217	-
mean =					0.1203	
st. dev =					0.0010	
pct. =					0.009	



NACA 25112

alpha = 9 deg
x_ac = 0.530 from te

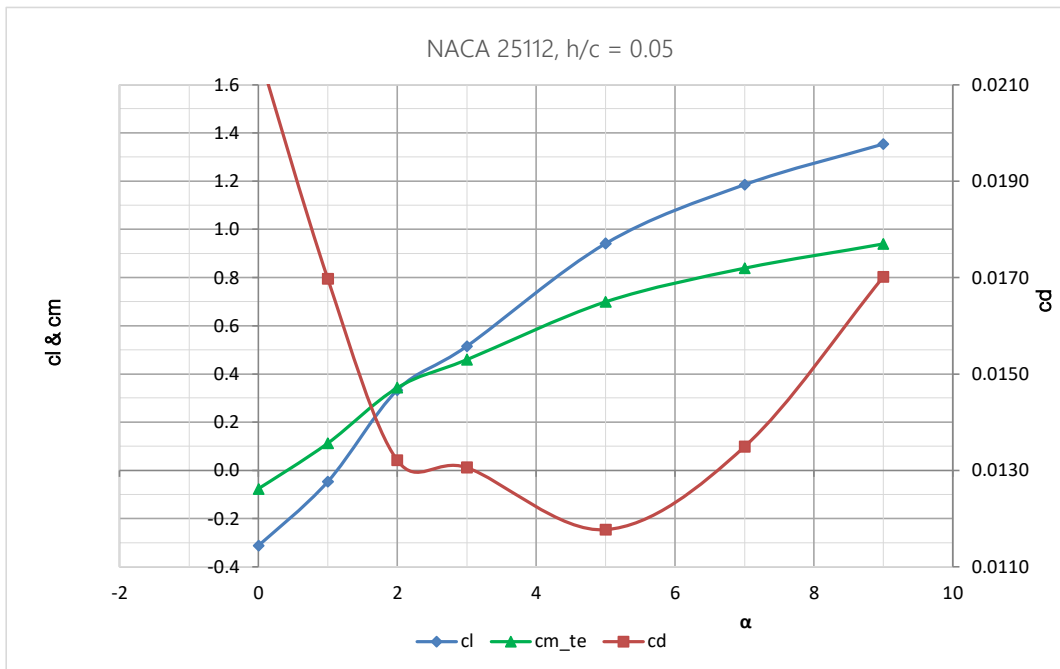
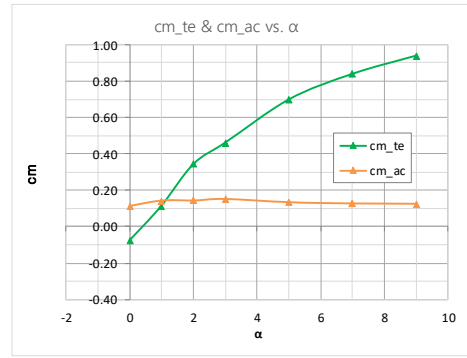
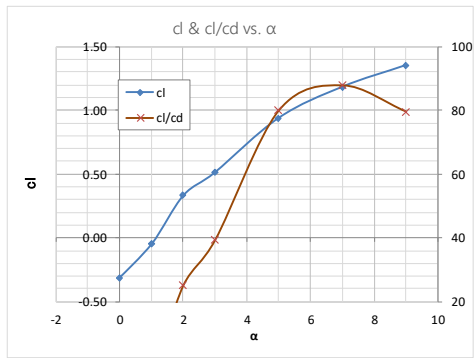
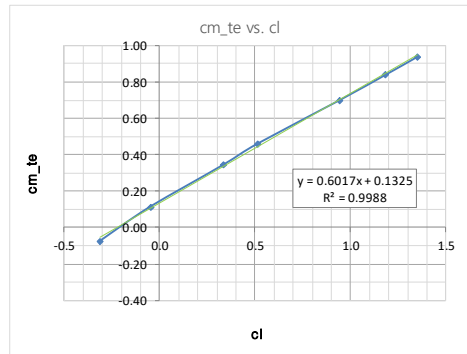
h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	1.354	0.01701	0.93915	79.6	0.2217	1.276
0.1	1.250	0.01672	0.8869	74.7	0.2247	1.198
0.2	1.153	0.01598	0.8337	72.1	0.2227	1.156
0.3	1.100	0.01631	0.8041	67.4	0.2211	1.081
0.5	1.062	0.01586	0.7842	67.0	0.2213	1.073
0.75	1.044	0.01629	0.7761	64.1	0.2227	1.027
1.0	1.039	0.01666	0.7753	62.4	0.2245	-
					mean =	0.2227
					st. dev =	0.0014
					pct. =	0.007



NACA 25112

$h/c = 0.05$
 $x_{ac} = 0.602$ from te

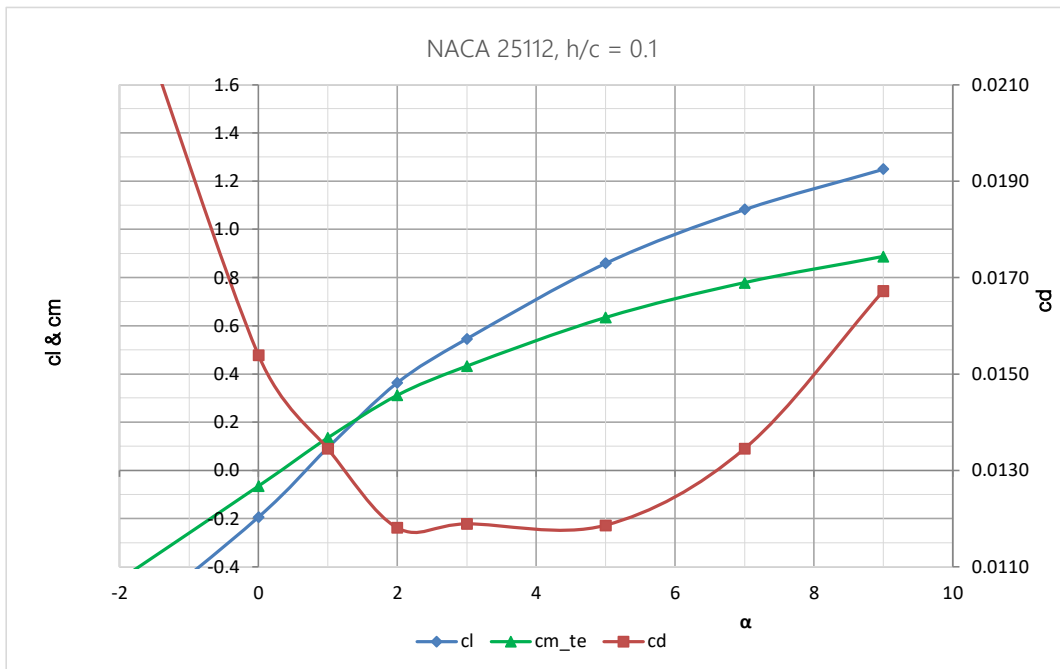
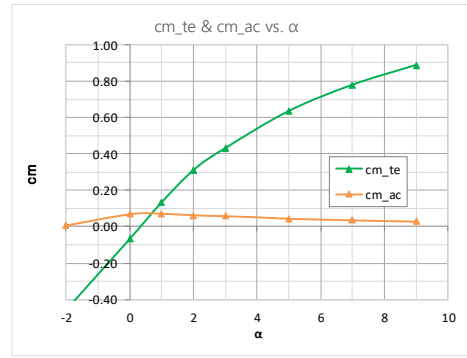
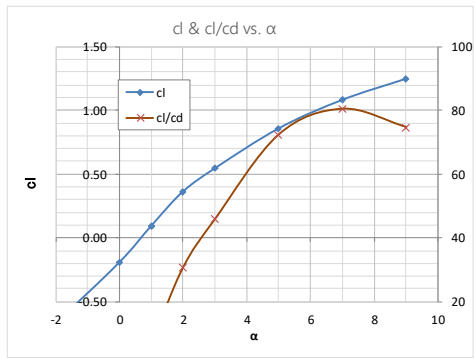
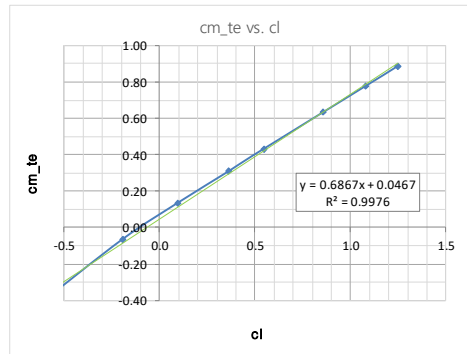
α	cl	cd	cm_te	cl/cd	cm_ac	
-2						
0	-0.3127	0.02170	-0.0769	-14.4	0.1113	-0.181
1	-0.0470	0.01697	0.1127	-2.8	0.1410	-0.035
2	0.3325	0.01321	0.3424	25.2	0.1422	0.316
3	0.5143	0.01306	0.4595	39.4	0.1499	0.495
5	0.941	0.01177	0.6988	80.0	0.1321	1.005
7	1.185	0.01349	0.8391	87.8	0.1257	1.104
9	1.354	0.01701	0.9392	79.6	0.1242	-
					mean =	0.1324
					st. dev =	0.0131
					pct. =	0.099



NACA 25112

$h/c = 0.1$
 $x_{ac} = 0.687$ from te

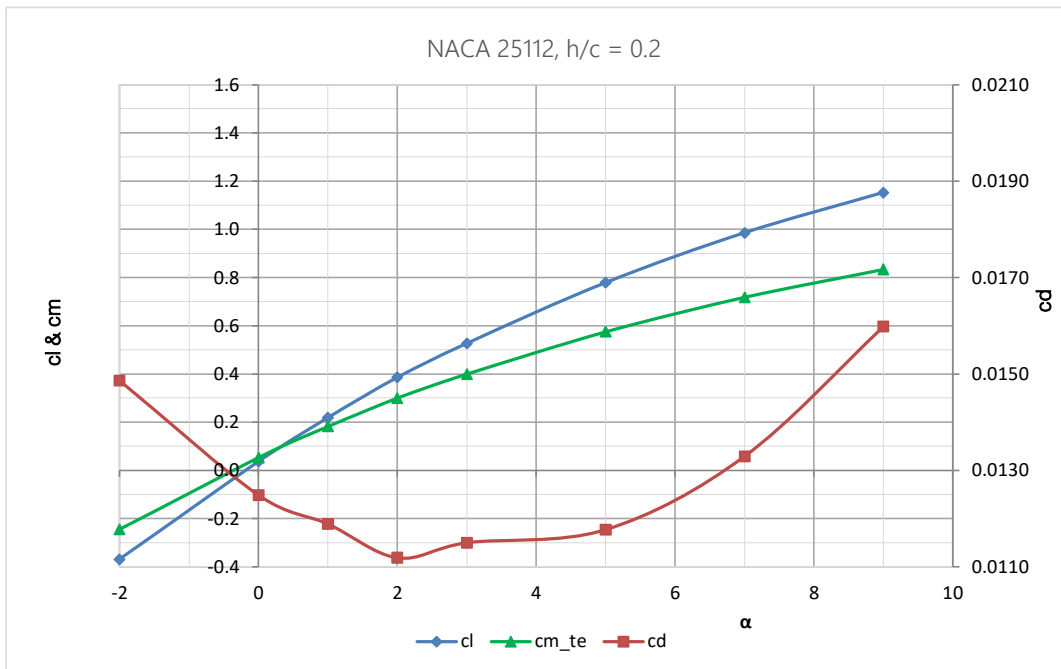
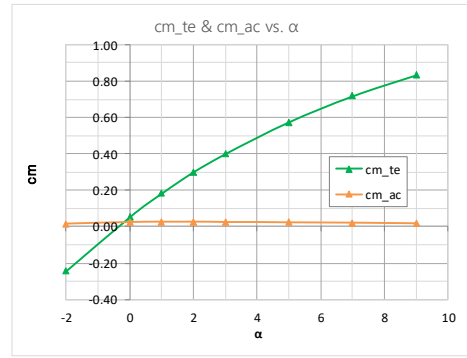
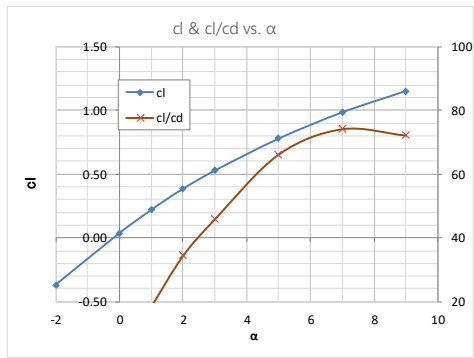
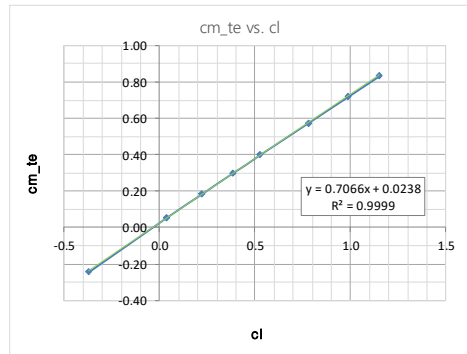
α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.6703	0.02358	-0.4535	-28.4	0.0070	-0.380
0	-0.1940	0.01539	-0.0650	-12.6	0.0683	-0.169
1	0.0943	0.01345	0.1349	7.0	0.0701	0.094
2	0.3632	0.01181	0.3112	30.8	0.0617	0.412
3	0.5450	0.01189	0.4324	45.8	0.0580	0.613
5	0.859	0.01186	0.6345	72.4	0.0443	0.969
7	1.082	0.01345	0.7785	80.4	0.0352	1.076
9	1.250	0.01672	0.8869	74.7	0.0285	-
					mean =	0.0466
					st. dev =	0.0221
					pct. =	0.473



NACA 25112

h/c = 0.2
x_ac = 0.707 from te

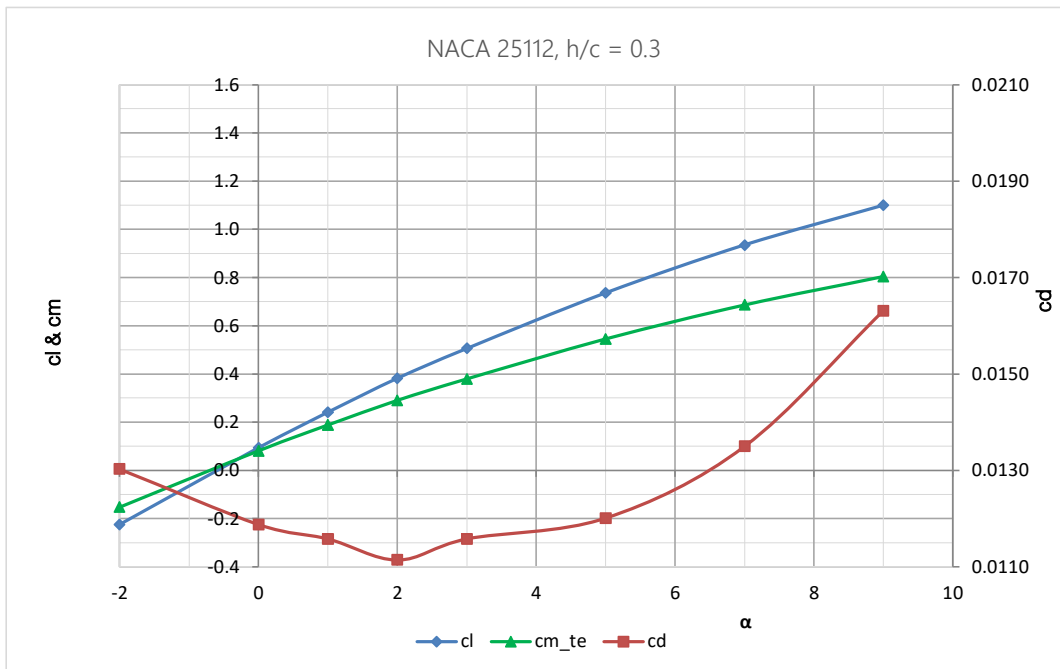
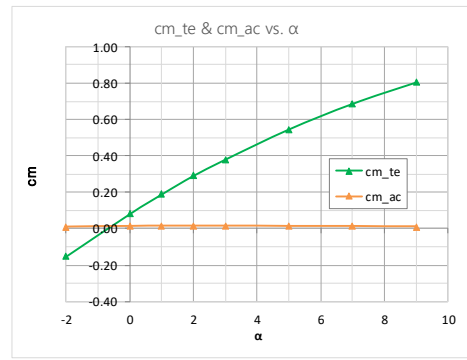
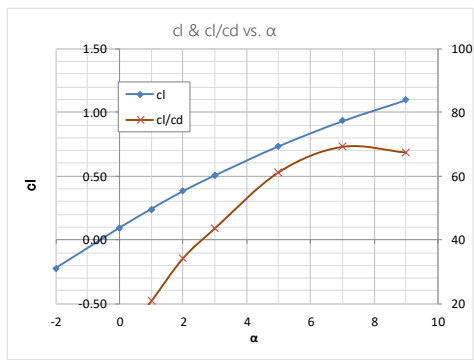
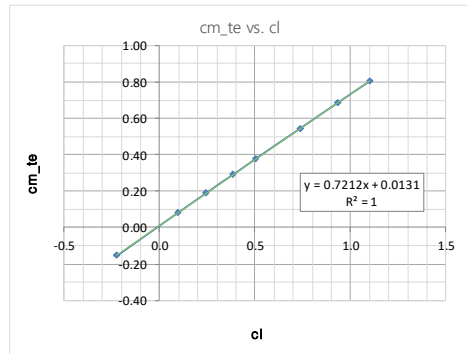
α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.3690	0.01486	-0.2446	-24.8	0.0163	-0.344
0	0.0369	0.01249	0.0529	3.0	0.0268	0.041
1	0.2186	0.01189	0.1822	18.4	0.0276	0.255
2	0.3851	0.01119	0.2994	34.4	0.0272	0.477
3	0.5270	0.01150	0.3992	45.8	0.0266	0.635
5	0.779	0.01177	0.5749	66.2	0.0241	0.918
7	0.985	0.01329	0.7180	74.1	0.0213	1.028
9	1.153	0.01598	0.8337	72.1	0.0187	-
					mean =	0.0236
					st. dev =	0.0043
					pct. =	0.184



NACA 25112

h/c = 0.3
x_ac = 0.721 from te

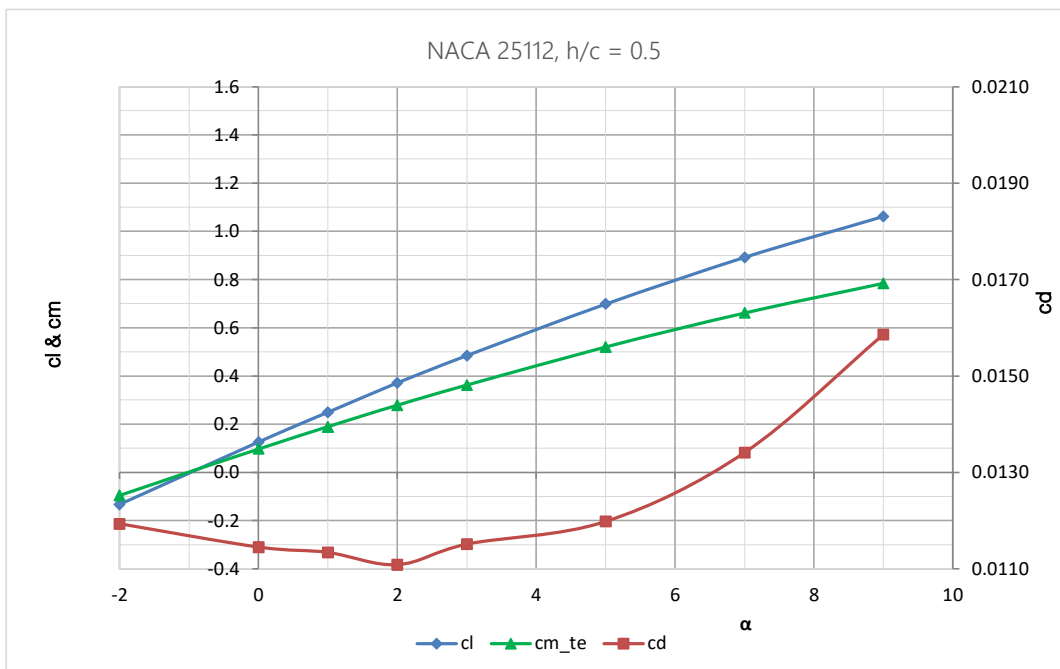
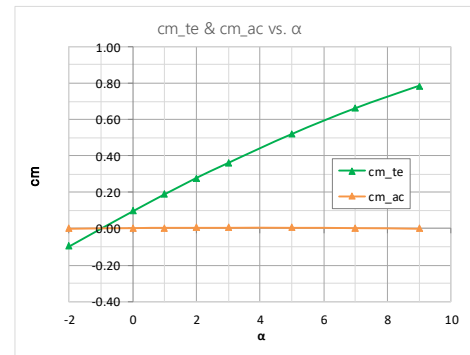
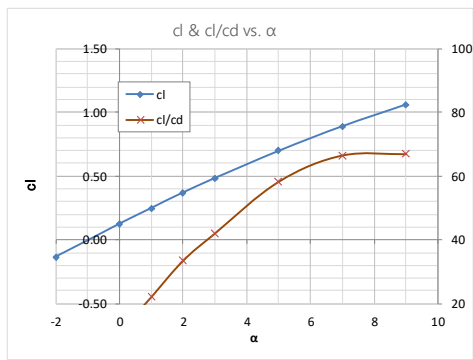
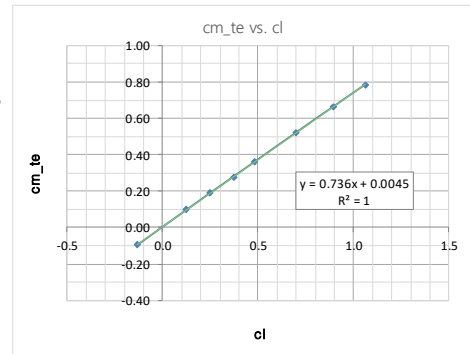
α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.2245	0.01303	-0.15234	-17.2	0.0095	-0.255
0	0.0935	0.01188	0.0815	7.9	0.0141	0.117
1	0.2410	0.01158	0.1885	20.8	0.0147	0.309
2	0.3822	0.01114	0.2903	34.3	0.0147	0.509
3	0.5058	0.01158	0.3797	43.7	0.0150	0.648
5	0.737	0.01201	0.5452	61.3	0.0140	0.910
7	0.935	0.01350	0.6865	69.2	0.0126	1.027
9	1.100	0.01631	0.8041	67.4	0.0110	-
					mean =	0.0132
					st. dev =	0.0020
					pct. =	0.153



NACA 25112

$h/c = 0.5$
 $x_{ac} = 0.736$ from te

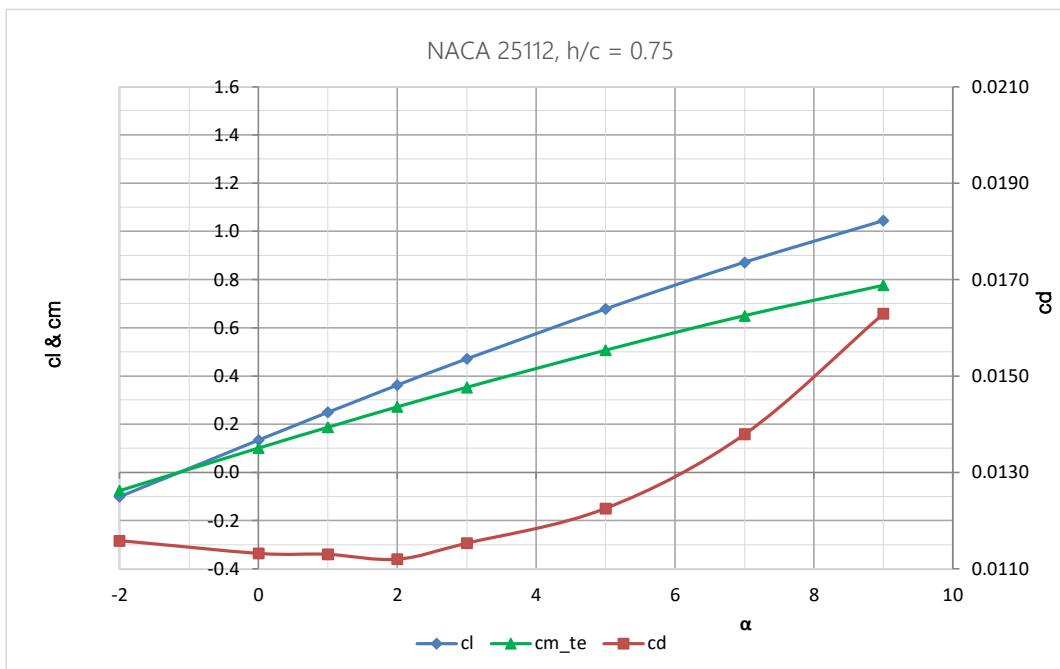
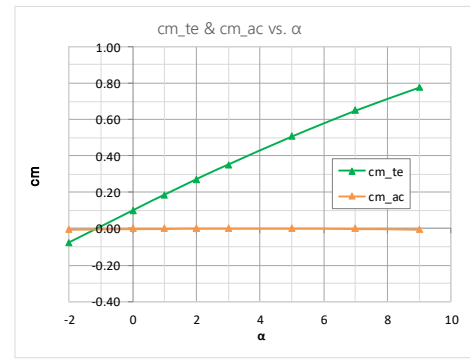
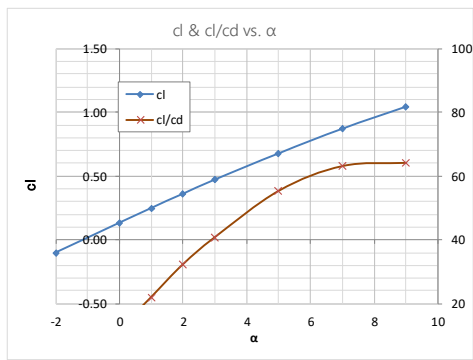
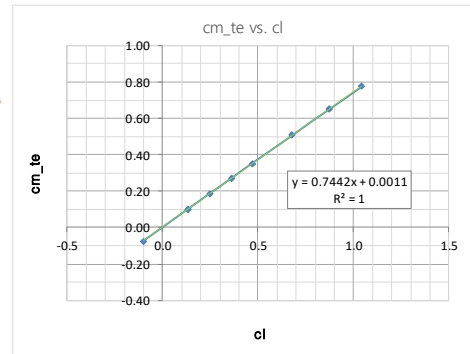
α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.1329	0.01193	-0.0954	-11.1	0.0024	-0.166
0	0.1257	0.01145	0.0972	11.0	0.0047	0.164
1	0.2500	0.01134	0.1892	22.0	0.0052	0.329
2	0.3713	0.01108	0.2788	33.5	0.0055	0.500
3	0.4841	0.01151	0.3620	42.1	0.0057	0.628
5	0.699	0.01198	0.5197	58.3	0.0055	0.871
7	0.892	0.01341	0.6609	66.5	0.0044	0.993
9	1.062	0.01586	0.7842	67.0	0.0026	-
					mean =	0.0045
					st. dev =	0.0013
					pct. =	0.293



NACA 25112

$h/c = 0.75$
 $x_{ac} = 0.744$ from te

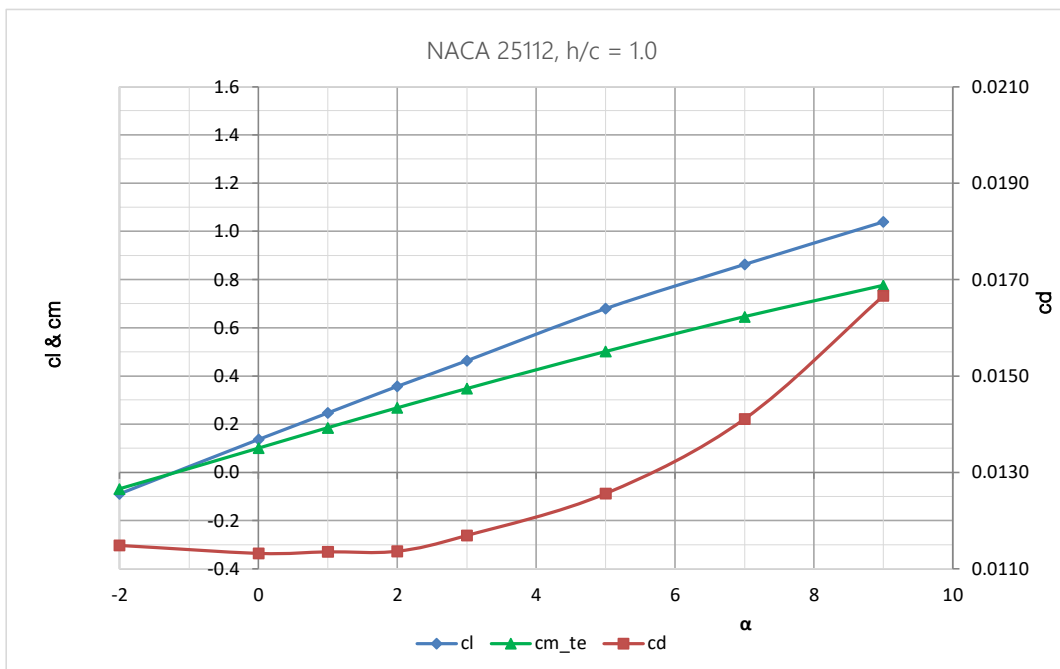
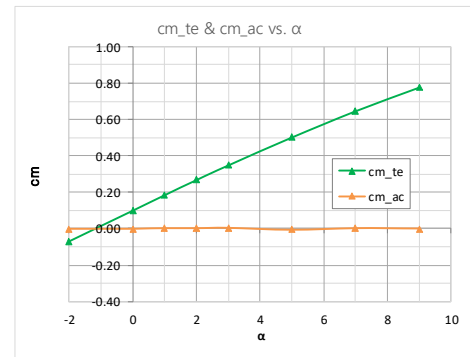
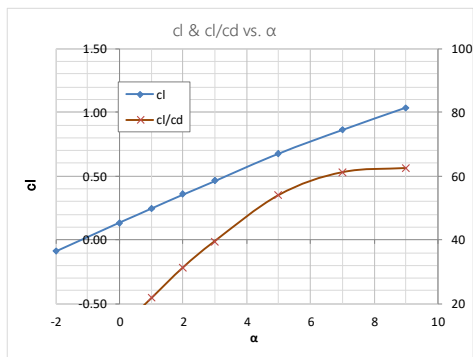
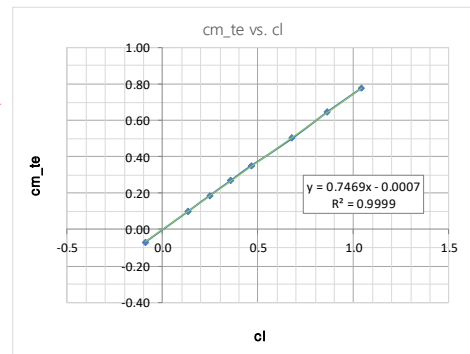
α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.1010	0.01158	-0.075905	-8.7	-0.0008	-0.136
0	0.1335	0.01132	0.1004	11.8	0.0011	0.184
1	0.2486	0.01130	0.1866	22.0	0.0016	0.343
2	0.3621	0.01120	0.2715	32.3	0.0021	0.505
3	0.4703	0.01153	0.3523	40.8	0.0024	0.636
5	0.678	0.01225	0.5068	55.3	0.0024	0.864
7	0.871	0.01379	0.6492	63.1	0.0013	0.985
9	1.044	0.01629	0.7761	64.1	-0.0007	-
					mean =	0.0012
					st. dev =	0.0013
					pct. =	1.086



NACA 25112

$h/c = 1.0$
 $x_{ac} = 0.747$ from te

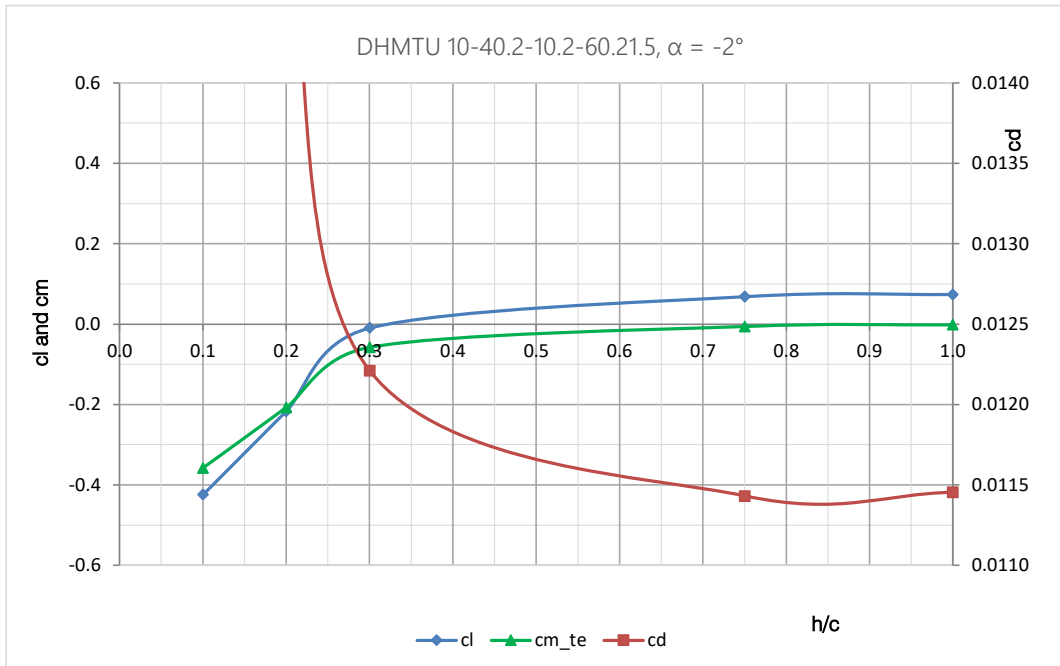
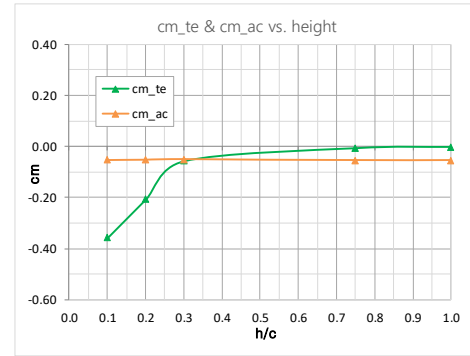
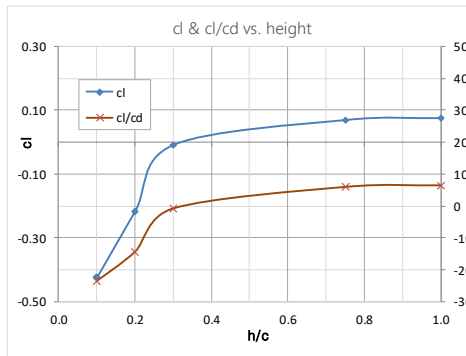
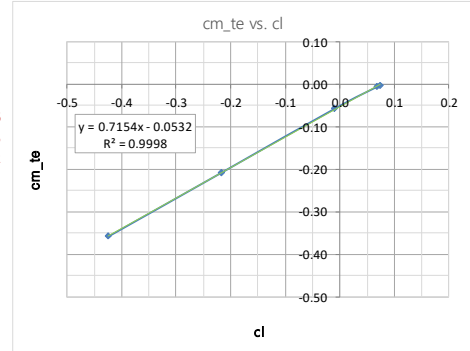
α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.0891	0.01148	-0.068678	-7.8	-0.0021	-0.124
0	0.1362	0.01132	0.1004	12.0	-0.0013	0.193
1	0.2463	0.01135	0.1846	21.7	0.0006	0.348
2	0.3565	0.01136	0.2675	31.4	0.0012	0.503
3	0.4628	0.01169	0.3474	39.6	0.0017	0.635
5	0.679	0.01256	0.5014	54.0	-0.0056	0.866
7	0.863	0.01410	0.6453	61.2	0.0009	0.980
9	1.039	0.01666	0.7753	62.4	-0.0010	-
					mean =	-0.0007
					st. dev =	0.0024
					pct. =	3.409



8.9 Appendix – Detailed Results DHMTU

DHMTU 10-40.2-10.2-60.21.5

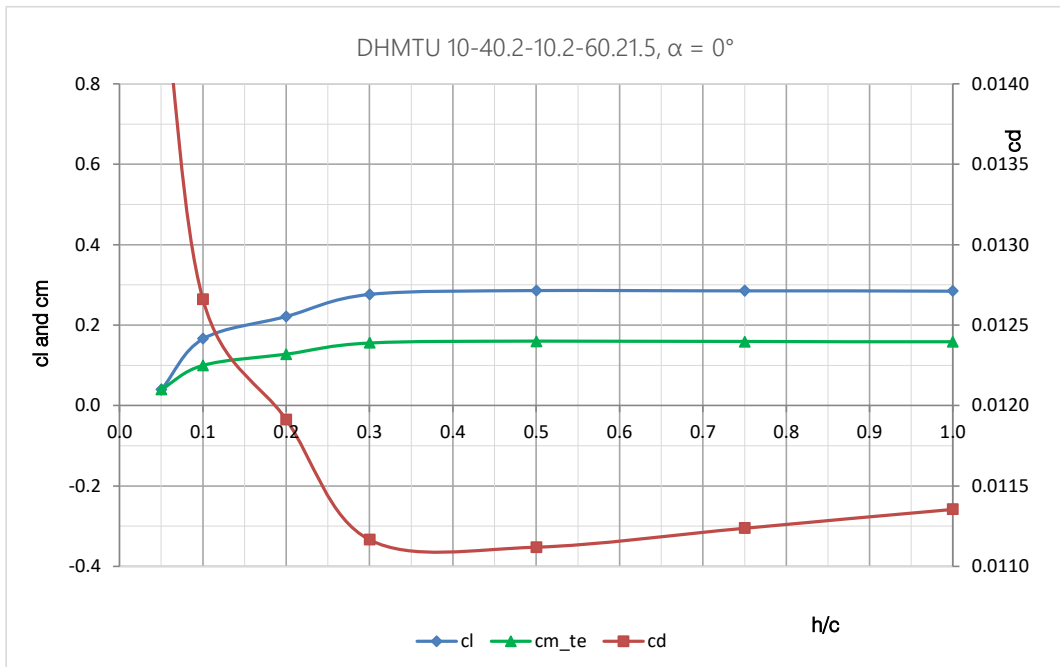
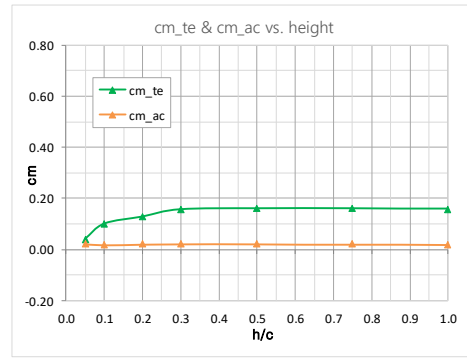
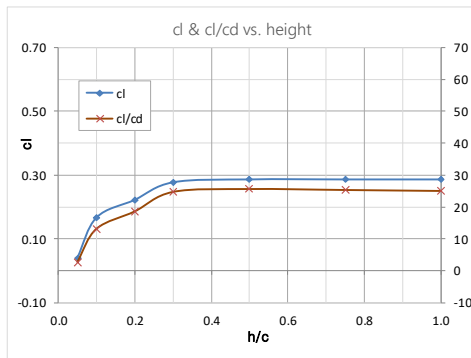
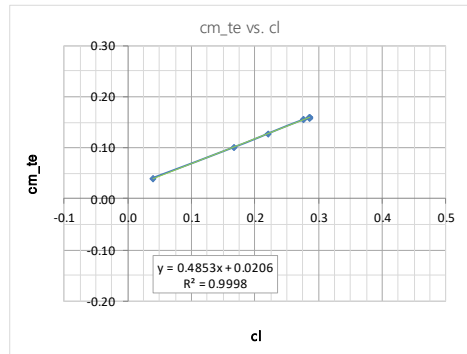
alpha =	-2	deg				
x_ac =	0.716	from te				
h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05						
0.1	-0.4240	0.01799	-0.3576	-23.6	-0.0540	-3.636
0.2	-0.2168	0.01510	-0.2074	-14.4	-0.0522	-2.215
0.3	-0.0097	0.01221	-0.0573	-0.8	-0.0503	-0.122
0.5						
0.75	0.0685	0.01143	-0.0055	6.0	-0.0545	0.924
1.0	0.0742	0.01145	-0.0017	6.5	-0.0548	-
					mean =	-0.0532
					st. dev =	0.0019
					pct. =	0.036



DHMTU 10-40.2-10.2-60.21.5

alpha = 0 deg
x_ac = 0.485 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	0.0394	0.01472	0.04023	2.7	0.0211	0.107
0.1	0.1662	0.01266	0.1001	13.1	0.0195	0.523
0.2	0.2213	0.01191	0.1279	18.6	0.0205	0.740
0.3	0.2765	0.01117	0.1556	24.8	0.0215	0.987
0.5	0.2859	0.01112	0.1597	25.7	0.0211	1.024
0.75	0.2854	0.01124	0.1590	25.4	0.0206	1.012
1.0	0.2850	0.01136	0.1584	25.1	0.0201	-
					mean =	0.0206
					st. dev =	0.0007
					pct. =	0.033

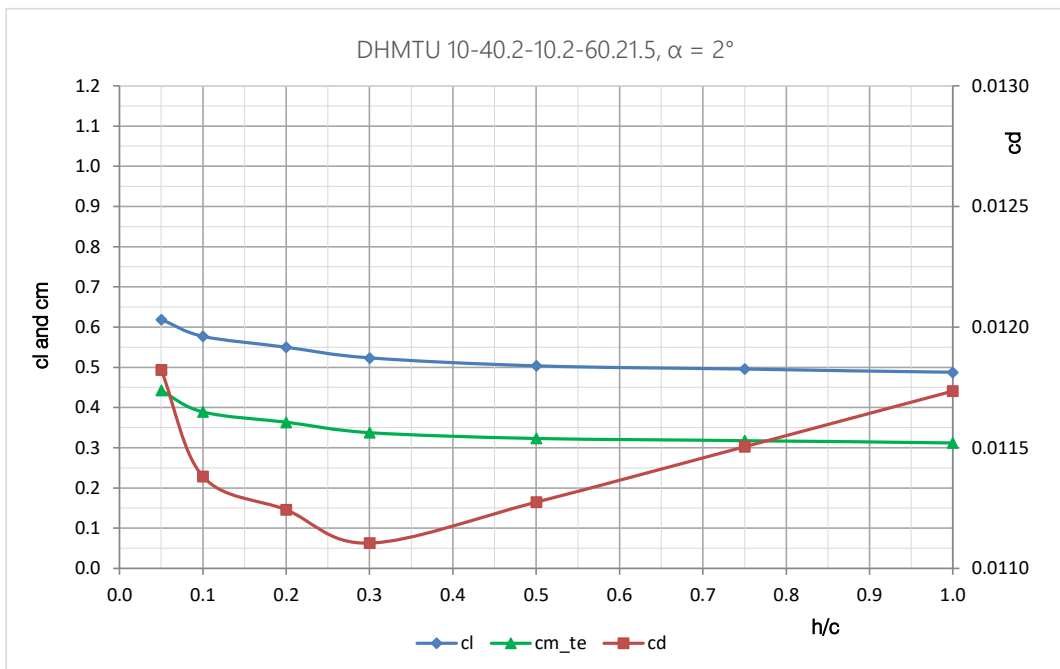
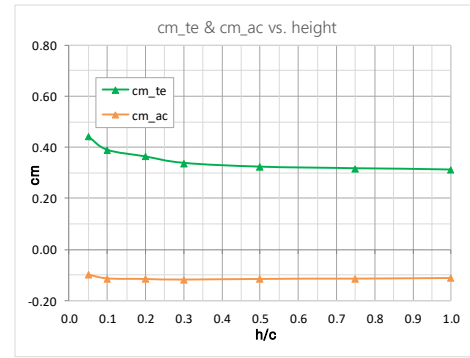
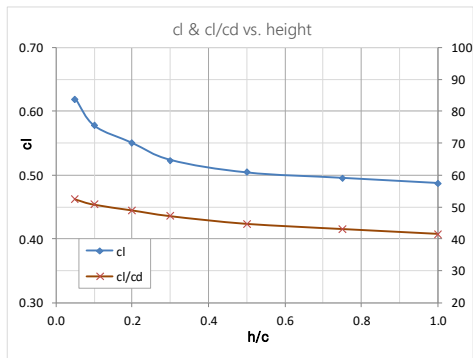
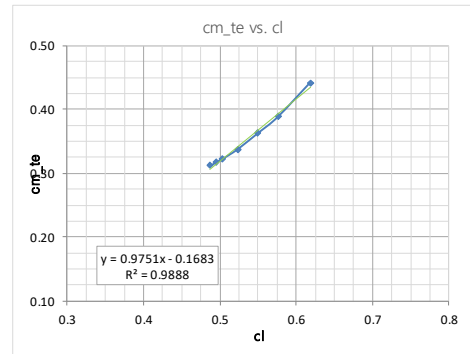


DHMTU 10-40.2-10.2-60.21.5

alpha = 2 deg
x_ac = 0.873 from te

h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	0.6187	0.01182	0.441907	52.3	-0.0982	1.260
0.1	0.5769	0.01138	0.3890	50.7	-0.1147	1.221
0.2	0.5501	0.01124	0.3633	48.9	-0.1170	1.178
0.3	0.5232	0.01110	0.3376	47.1	-0.1192	1.135
0.5	0.5037	0.01127	0.3229	44.7	-0.1168	1.076
0.75	0.4956	0.01150	0.3174	43.1	-0.1152	1.037
1.0	0.4874	0.01174	0.3119	41.5	-0.1136	-

mean = -0.1135
st. dev = 0.0070
pct. = 0.062

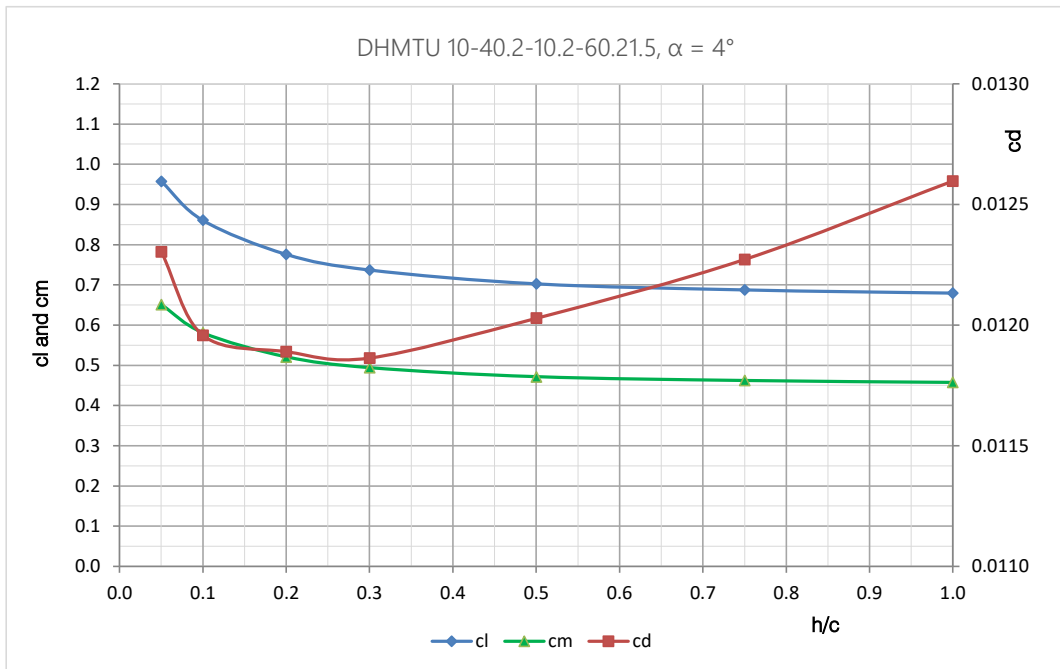
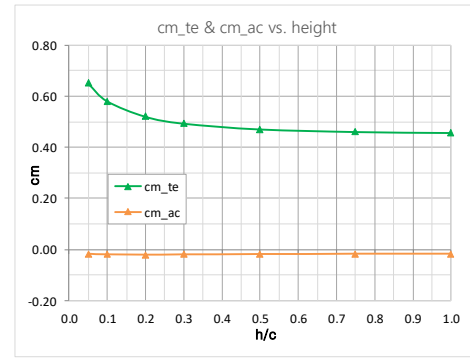
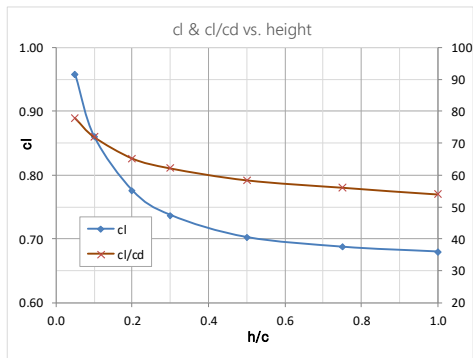
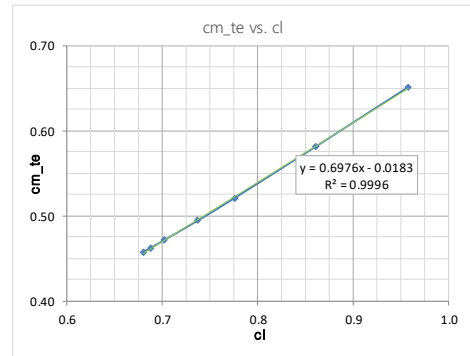


DHMTU 10-40.2-10.2-60.21.5

alpha = 4 deg
x_ac = 0.698 from te

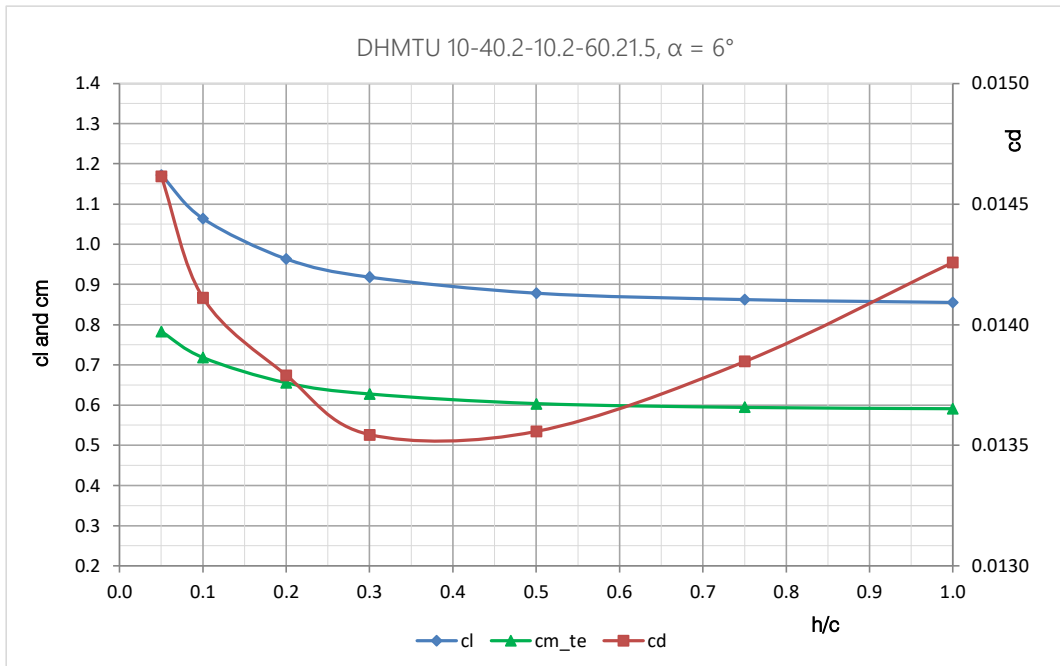
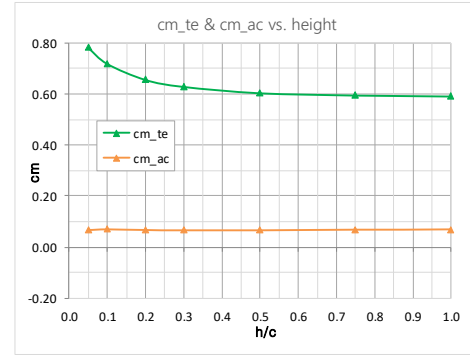
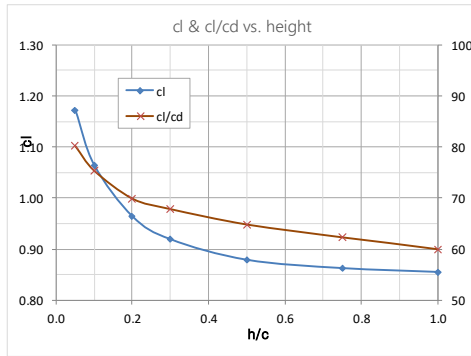
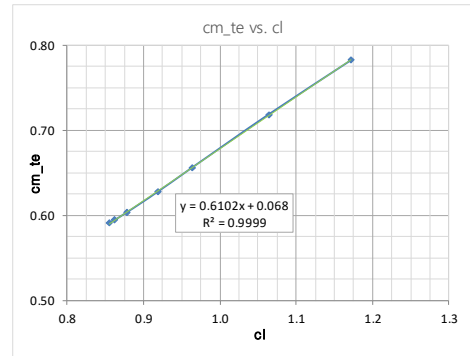
h/c	cl	cd	cm	cl/cd	cm_ac	
0.05	0.9575	0.01230	0.6511	77.8	-0.0172	1.443
0.1	0.8606	0.01196	0.5811	72.0	-0.0196	1.334
0.2	0.7757	0.01189	0.5209	65.2	-0.0205	1.209
0.3	0.7369	0.01186	0.4943	62.1	-0.0201	1.151
0.5	0.7023	0.01203	0.4715	58.4	-0.0187	1.082
0.75	0.6872	0.01227	0.4620	56.0	-0.0176	1.038
1.0	0.6796	0.01260	0.4575	53.9	-0.0168	-

mean = -0.0186
st. dev = 0.0015
pct. = 0.079



DHMTU 10-40.2-10.2-60.21.5

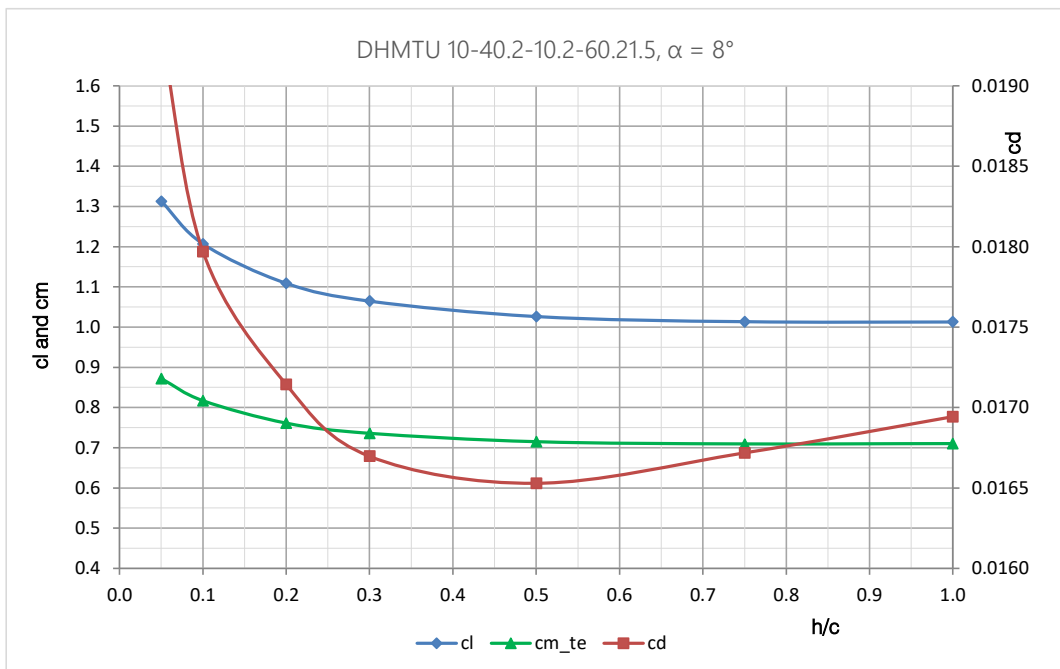
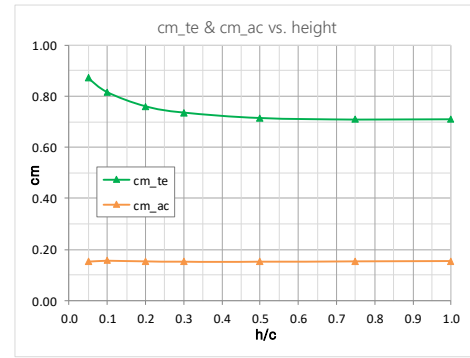
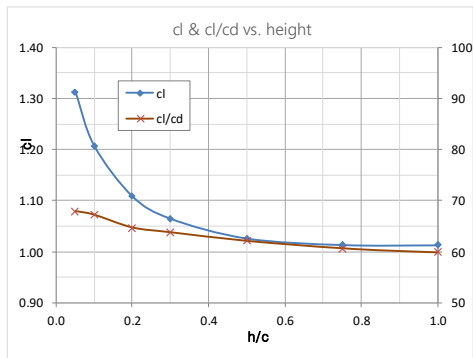
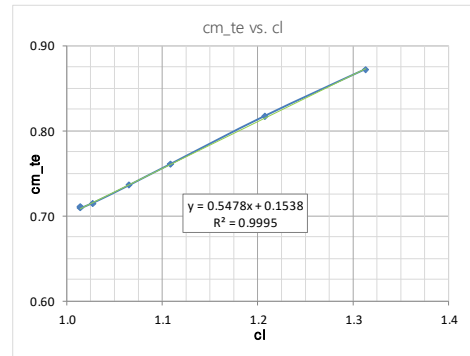
alpha =	6	deg				
x_ac =	0.610	from te				
h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	1.172	0.01461	0.7825	80.2	0.0678	1.337
0.1	1.064	0.01411	0.7183	75.4	0.0694	1.257
0.2	0.964	0.01379	0.6558	69.9	0.0679	1.165
0.3	0.9185	0.01354	0.6275	67.8	0.0673	1.131
0.5	0.8785	0.01356	0.6034	64.8	0.0675	1.081
0.75	0.8625	0.01385	0.5945	62.3	0.0683	1.039
1.0	0.8550	0.01426	0.5907	60.0	0.0691	-
				mean =	0.0682	
				st. dev =	0.0008	
				pct. =	0.012	



DHMTU 10-40.2-10.2-60.21.5

alpha = 8 deg
x_ac = 0.548 from te

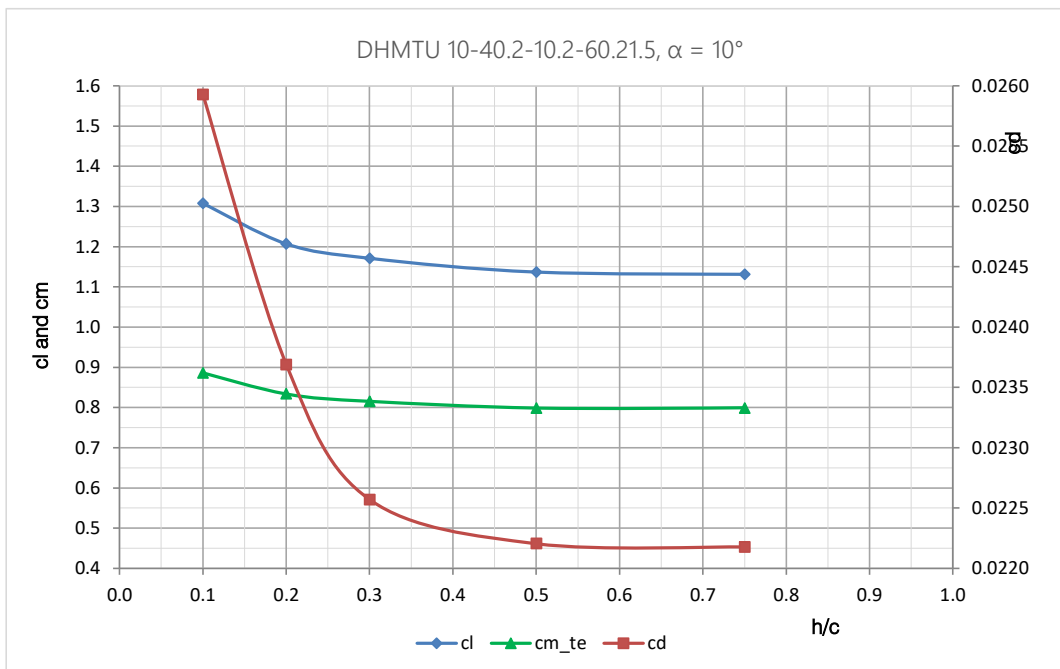
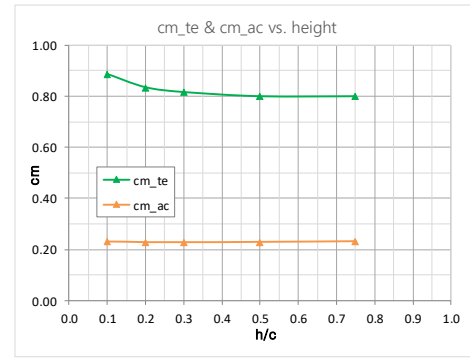
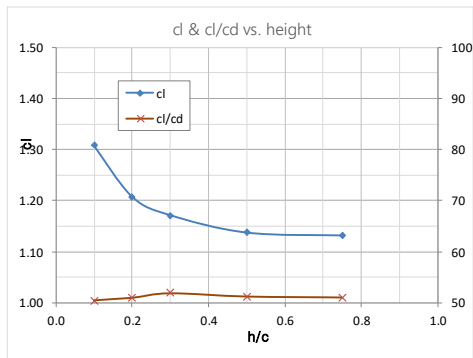
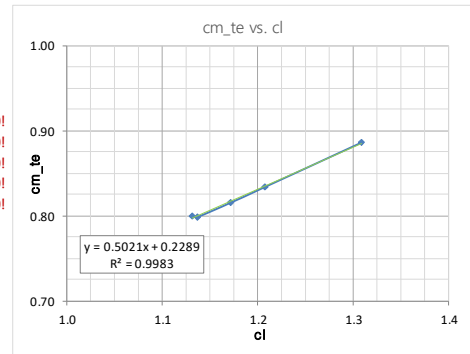
h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05	1.313	0.01933	0.8718	67.9	0.1525	1.135
0.1	1.207	0.01797	0.8170	67.2	0.1556	1.123
0.2	1.109	0.01714	0.7611	64.7	0.1535	1.081
0.3	1.065	0.01670	0.7358	63.8	0.1523	1.066
0.5	1.026	0.01653	0.7147	62.1	0.1523	1.038
0.75	1.013	0.01672	0.7090	60.6	0.1537	1.014
1.0	1.013	0.01694	0.7104	59.8	0.1551	-
					mean =	0.1536
					st. dev =	0.0013
					pct. =	0.009



DHMTU 10-40.2-10.2-60.21.5

alpha = 10 deg
x_ac = 0.502 from te

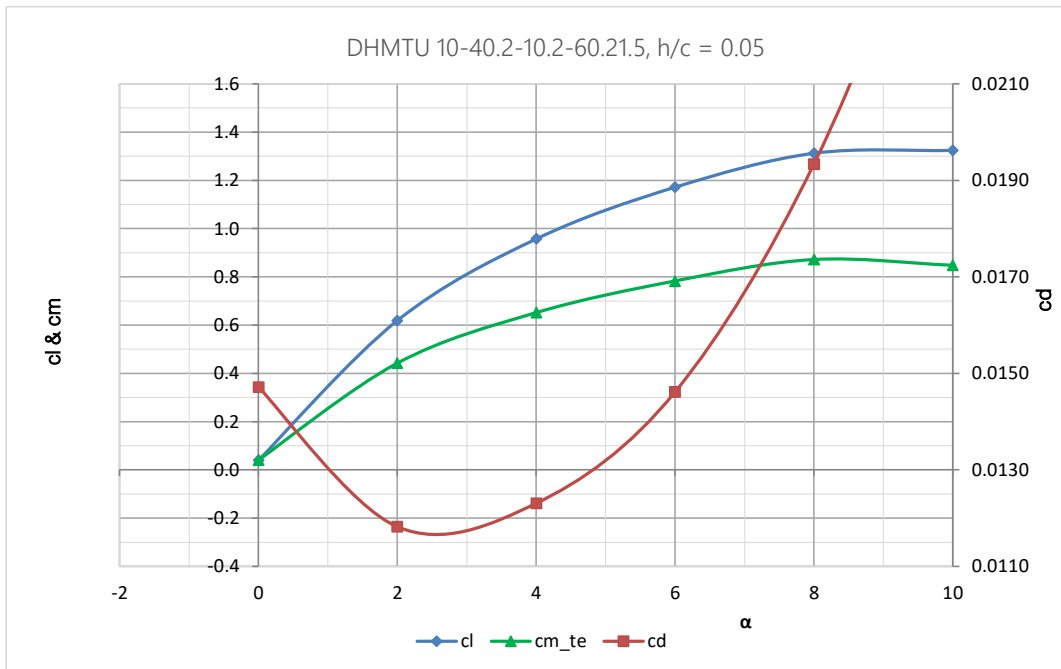
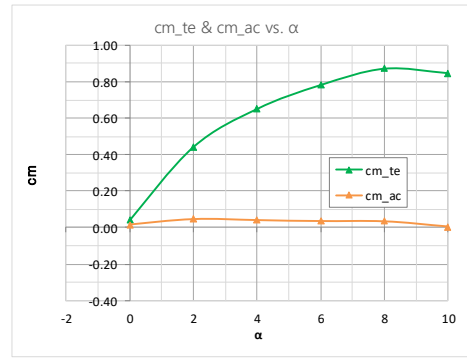
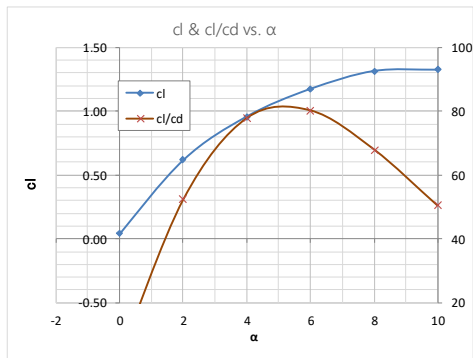
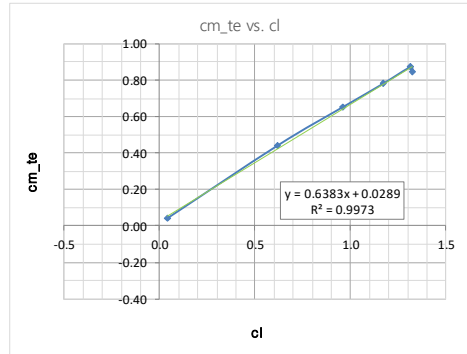
h/c	cl	cd	cm_te	cl/cd	cm_ac	
0.05						
0.1	1.308	0.02593	0.8863	50.4	0.2298	#DIV/0!
0.2	1.207	0.02369	0.8340	51.0	0.2280	#DIV/0!
0.3	1.171	0.02257	0.8154	51.9	0.2276	#DIV/0!
0.5	1.137	0.02221	0.7990	51.2	0.2283	#DIV/0!
0.75	1.131	0.02218	0.7992	51.0	0.2312	#DIV/0!
1.0						
					mean =	0.2290
					st. dev =	0.0015
					pct. =	0.006



DHMTU 10-40.2-10.2-60.21.5

$h/c = 0.05$
 $x_{ac} = 0.638$ from te

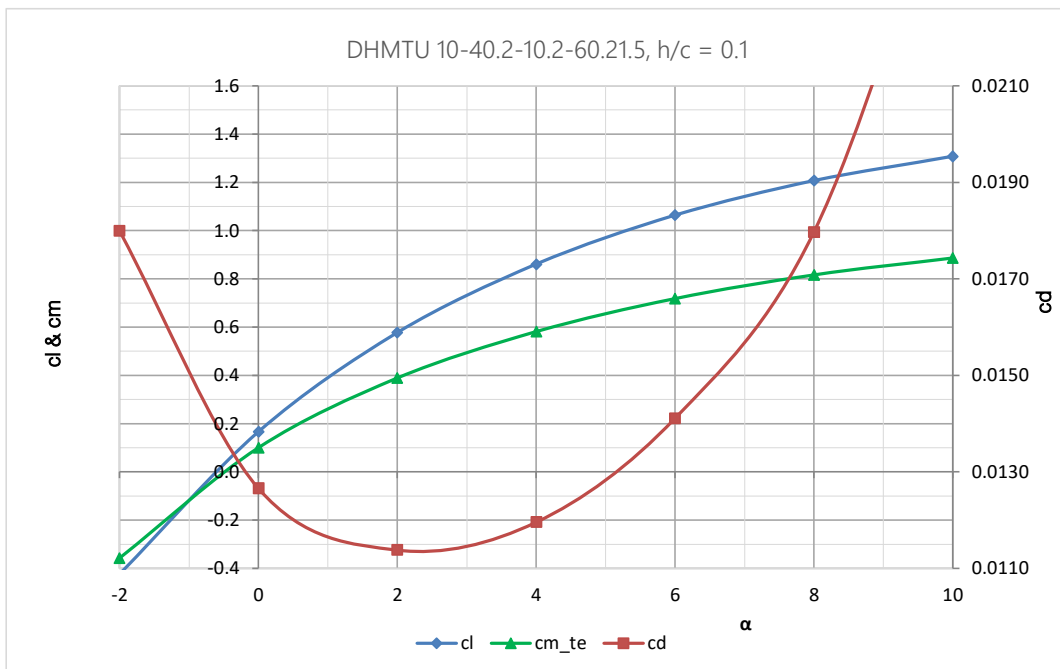
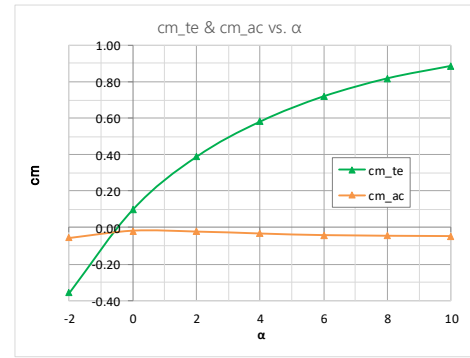
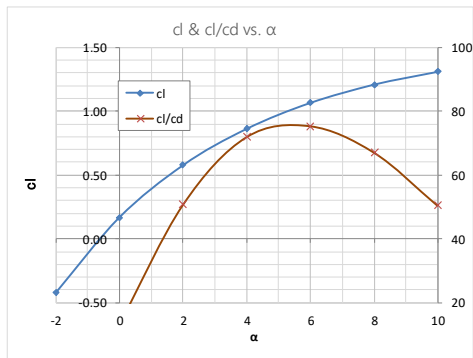
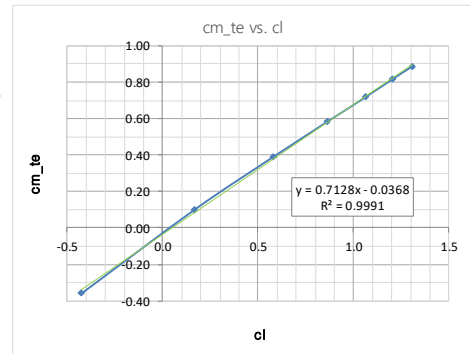
α	cl	cd	cm_te	cl/cd	cm_ac	
-2						
0	0.0394	0.01472	0.0402	2.7	0.0151	0.053
2	0.6187	0.01182	0.4419	52.3	0.0472	1.040
4	0.9575	0.01230	0.6511	77.8	0.0402	1.546
6	1.172	0.01461	0.7825	80.2	0.0350	1.593
8	1.313	0.01933	0.8718	67.9	0.0344	1.349
10	1.324	0.02630	0.8480	50.3	0.0033	-
						mean = 0.0292
						st. dev = 0.0166
						pct. = 0.568



DHMTU 10-40.2-10.2-60.21.5

$h/c = 0.1$
 $x_{ac} = 0.713$ from te

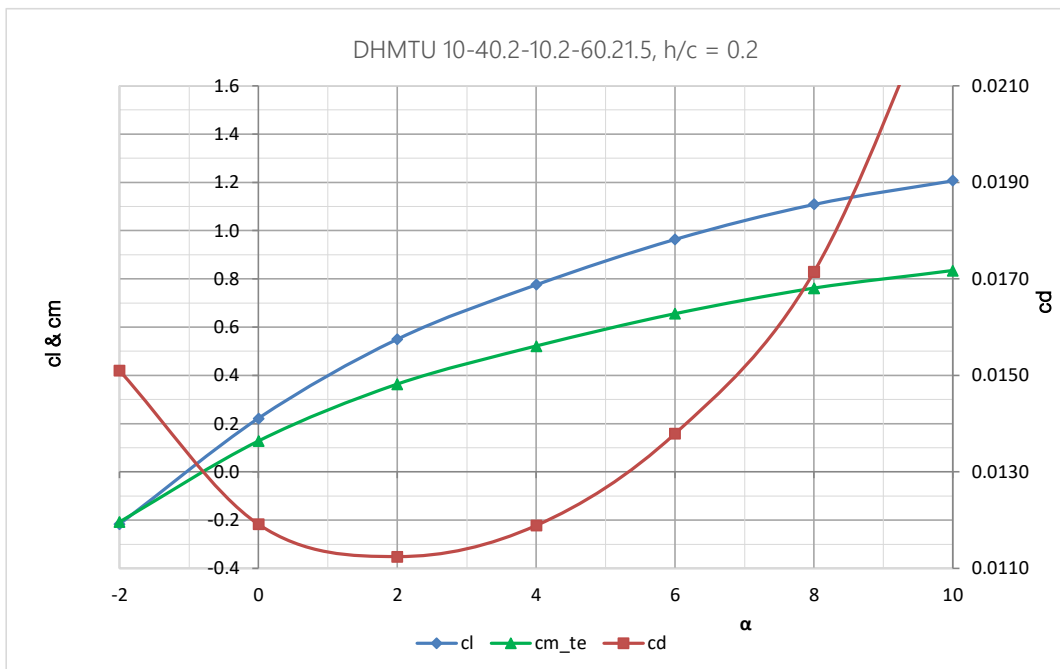
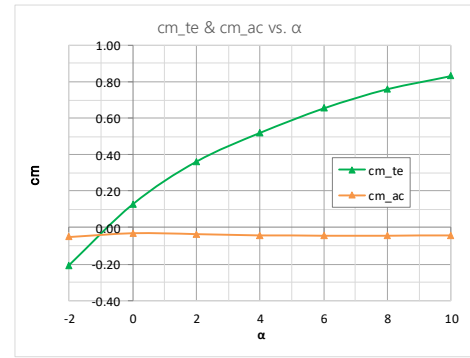
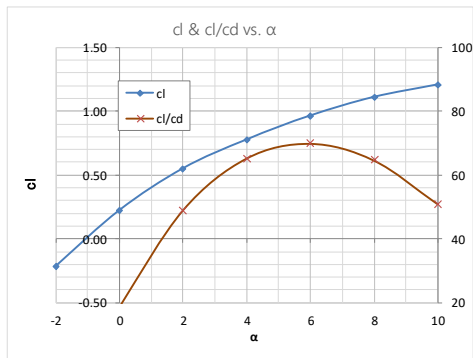
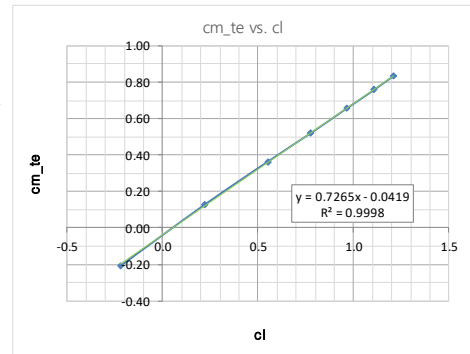
α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.4240	0.01799	-0.35759	-23.6	-0.0553	-0.467
0	0.1662	0.01266	0.1001	13.1	-0.0184	0.260
2	0.5769	0.01138	0.3890	50.7	-0.0224	1.005
4	0.8606	0.01196	0.5811	72.0	-0.0325	1.427
6	1.064	0.01411	0.7183	75.4	-0.0401	1.495
8	1.207	0.01797	0.8170	67.2	-0.0436	1.332
10	1.308	0.02593	0.8863	50.4	-0.0462	-
						mean = -0.0369
						st. dev = 0.0132
						pct. = 0.359



DHMTU 10-40.2-10.2-60.21.5

$h/c = 0.2$
 $x_{ac} = 0.726$ from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.2168	0.01510	-0.20743	-14.4	-0.0500	-0.282
0	0.2213	0.01191	0.1279	18.6	-0.0328	0.365
2	0.5501	0.01124	0.3633	48.9	-0.0361	0.960
4	0.7757	0.01189	0.5209	65.2	-0.0423	1.280
6	0.964	0.01379	0.6558	69.9	-0.0439	1.372
8	1.109	0.01714	0.7611	64.7	-0.0439	1.269
10	1.207	0.02369	0.8340	51.0	-0.0424	-
						mean = -0.0416
						st. dev = 0.0056
						pct. = 0.135

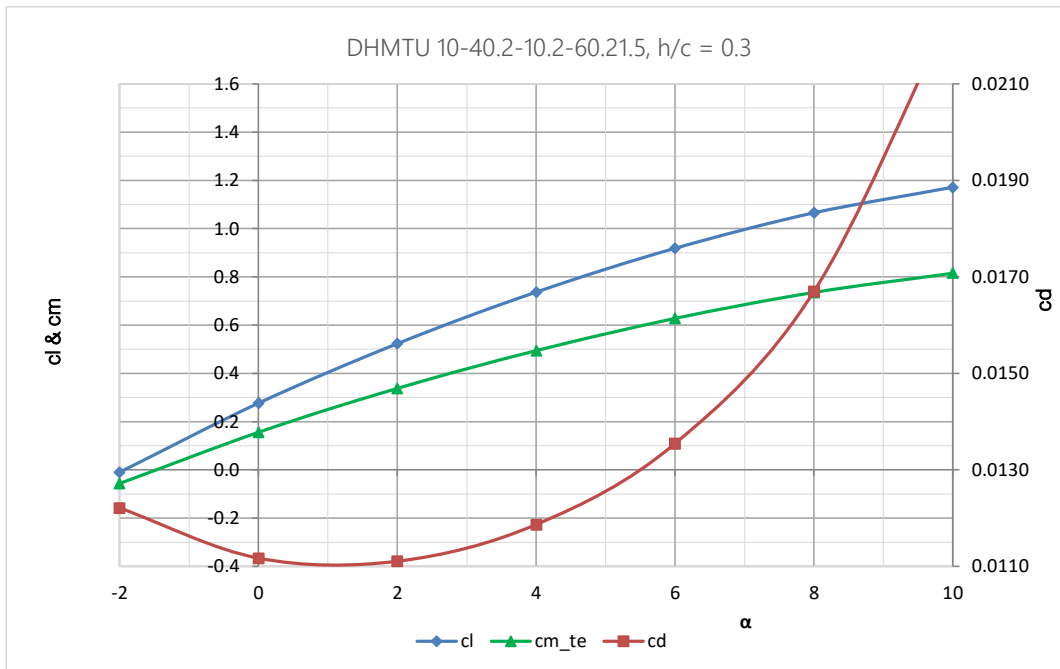
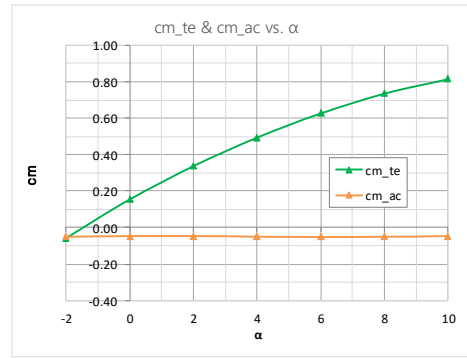
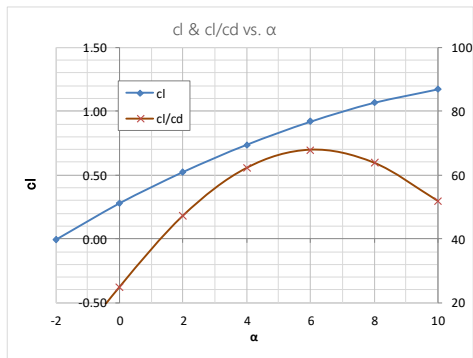
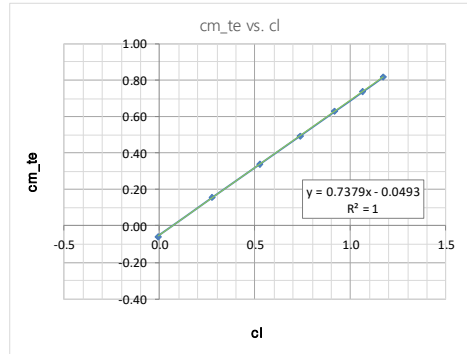


DHMTU 10-40.2-10.2-60.21.5

$h/c = 0.3$
 $x_{ac} = 0.738$ from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	-0.0097	0.01221	-0.05727	-0.8	-0.0501	-0.015
0	0.2765	0.01117	0.1556	24.8	-0.0484	0.477
2	0.5232	0.01110	0.3376	47.1	-0.0486	0.908
4	0.7369	0.01186	0.4943	62.1	-0.0495	1.197
6	0.918	0.01354	0.6275	67.8	-0.0503	1.307
8	1.065	0.01670	0.7358	63.8	-0.0500	1.229
10	1.171	0.02257	0.8154	51.9	-0.0487	-

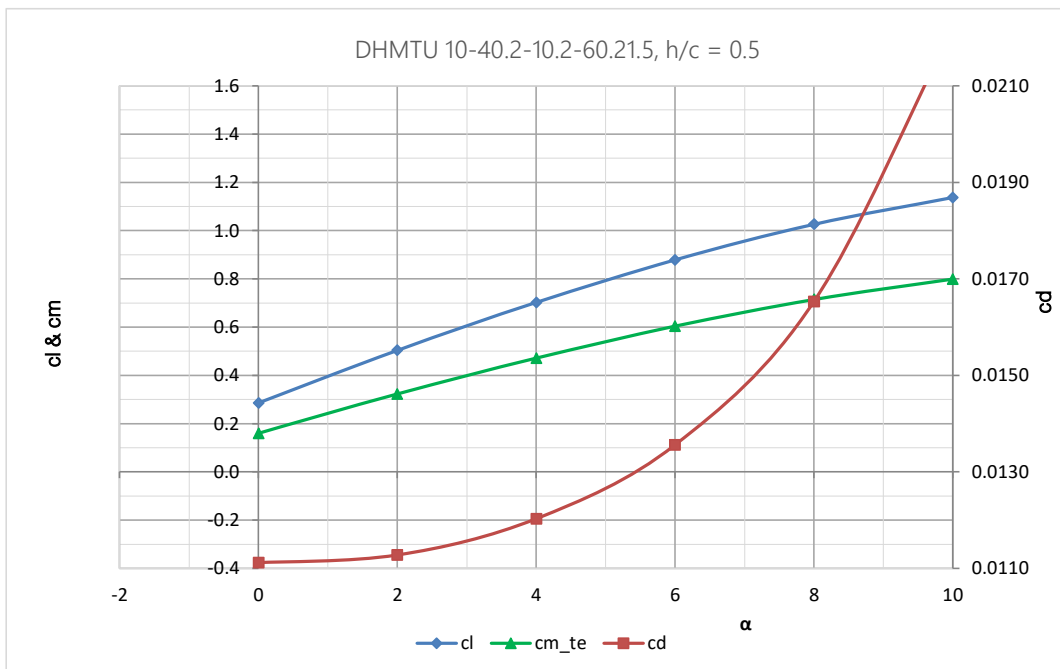
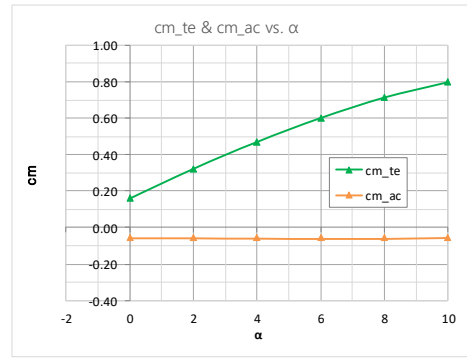
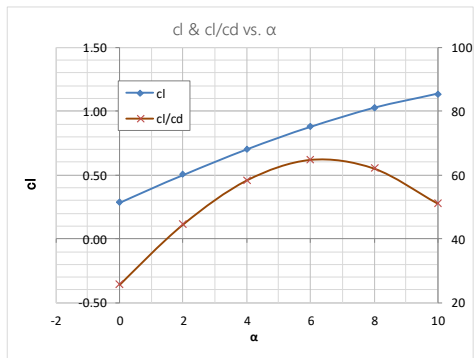
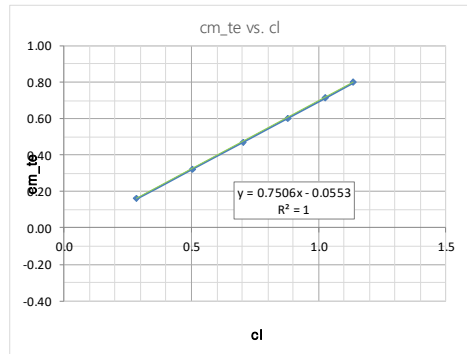
mean = -0.0494
 st. dev = 0.0008
 pct. = 0.016



DHMTU 10-40.2-10.2-60.21.5

$h/c = 0.5$
 $x_{ac} = 0.751$ from te

α	cl	cd	cm_te	cl/cd	cm_ac	
0	0.2859	0.01112	0.1597	25.7	-0.0550	0.502
2	0.5037	0.01127	0.3229	44.7	-0.0554	0.873
4	0.7023	0.01203	0.4715	58.4	-0.0559	1.141
6	0.878	0.01356	0.6034	64.8	-0.0563	1.266
8	1.026	0.01653	0.7147	62.1	-0.0560	1.213
10	1.137	0.02221	0.7990	51.2	-0.0547	-
					mean =	-0.0556
					st. dev =	0.0006
					pct. =	0.012

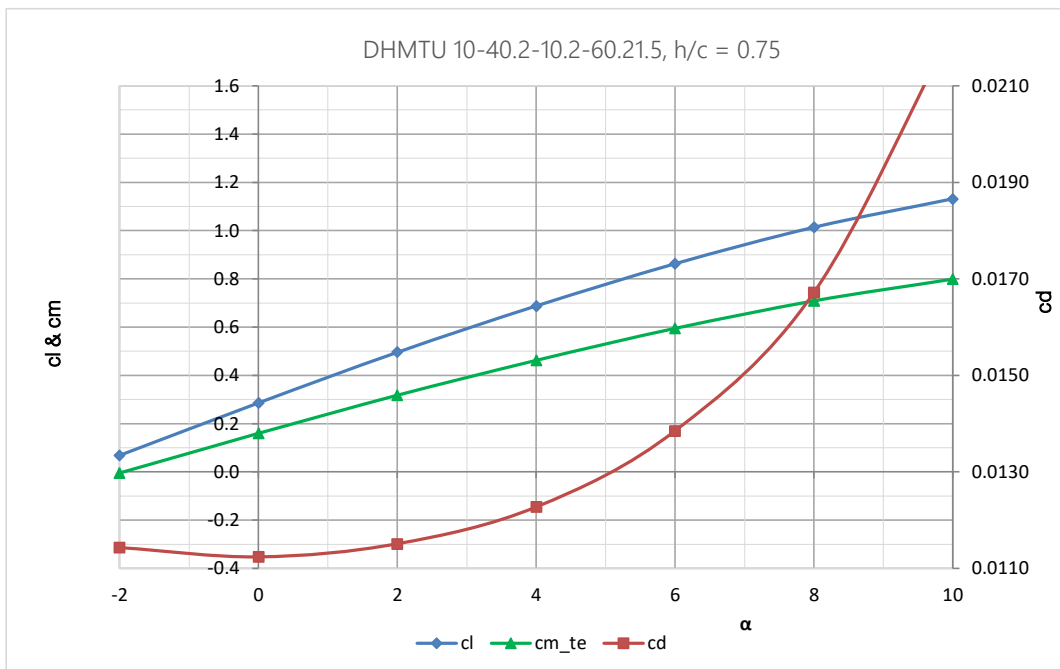
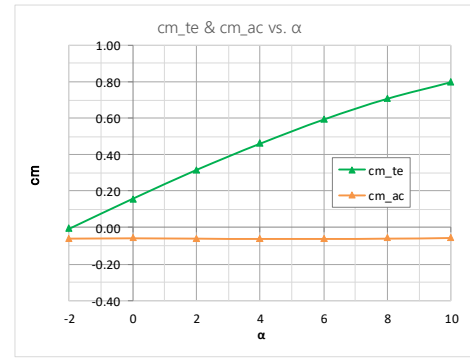
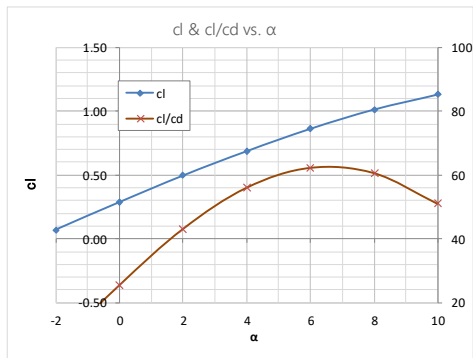
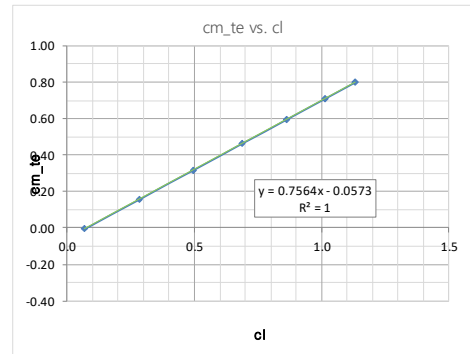


DHMTU 10-40.2-10.2-60.21.5

$h/c = 0.75$
 $x_{ac} = 0.756$ from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	0.0685	0.01143	-0.005517	6.0	-0.0573	0.117
0	0.2854	0.01124	0.1590	25.4	-0.0568	0.498
2	0.4956	0.01150	0.3174	43.1	-0.0572	0.844
4	0.6872	0.01227	0.4620	56.0	-0.0575	1.098
6	0.863	0.01385	0.5945	62.3	-0.0576	1.221
8	1.013	0.01672	0.7090	60.6	-0.0571	1.188
10	1.131	0.02218	0.7992	51.0	-0.0561	-

mean = -0.0571
 st. dev = 0.0005
 pct. = 0.009



DHMTU 10-40.2-10.2-60.21.5

$h/c = 1$
 $x_{ac} = 0.759$ from te

α	cl	cd	cm_te	cl/cd	cm_ac	
-2	0.0742	0.01145	-0.001698	6.5	-0.0580	0.126
0	0.2850	0.01136	0.1584	25.1	-0.0579	0.488
2	0.4874	0.01174	0.3119	41.5	-0.0580	0.808
4	0.6796	0.01260	0.4575	53.9	-0.0582	1.050
6	0.855	0.01426	0.5907	60.0	-0.0582	1.167
8	1.013	0.01694	0.7104	59.8	-0.0587	1.164
10	1.139	0.02216	0.8060	51.4	-0.0583	-
					mean =	-0.0582
					st. dev =	0.0002
					pct. =	0.004

