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Andrew Chadwick



Crosswind Aerodynamics of Sports Utility Vehicles

Supervisor: Kevin Garry

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Abstract

Crosswind gusts have a continuous influence on the ride and handling of road vehicles. At low speeds the effect is negligible but as both car and wind speeds increase there is a reduction in refinement, ride quality is degraded and it becomes tiring to drive. Future environmental legislation concerning the reduction of carbon dioxide emissions will lead to a lighter road vehicle and a corresponding increase in crosswind sensitivity.

The aerodynamicist's approach to understanding the fluid flow around a vehicle when subjected to a crosswind has conventionally been through steady state model tests where aerodynamic force and moment data are taken for different yaw angles. The accuracy of this data has previously been questioned because of a lack of simulation of the transient nature of the crosswind gust. Additionally, although force and moment data can tell the aerodynamicist which are the principle loads influencing a vehicles response in a crosswind, they fail to identify the specific regions on the vehicle that contribute to these aerodynamic loads. This can only be achieved by pressure mapping the model surface and although such a technique has been employed during steady state tests, no research has been presented with the correct modeling of the transient crosswind gust.

To gain an initial understanding of the complex time dependent and separated flow fields around bluff vehicles, such as sports utility vehicles, when subjected to a crosswind, aerodynamic force, moment and surface pressure data of simple geometric shapes has been collected on the Cranfield crosswind track facility. Steady state data has been obtained from conventional wind tunnel tests and compared with the transient data. Unique pressure animations identify the growth and collapse of vortices on the leeward face as the primary transient characteristic and which produce peak aerodynamic yawing moments up to double that seen in the steady state.

Acknowledgments

The author would like to thank Kevin Garry for his thoughtful guidance, supervision and assistance throughout this project. I am also very grateful to my industrial supervisor Jeff Howell who provided an understanding of the crosswind problem faced by industry and also to Rover Group who co financed this project with the EPSRC and whose continued involvement supports the development of the Cranfield crosswind track facility. Previous Ph.D. student Roger Macklin provided advice in the initial stages of this project and Scott Shaw helped in the application of data to the Fieldview CFD post-processing package.

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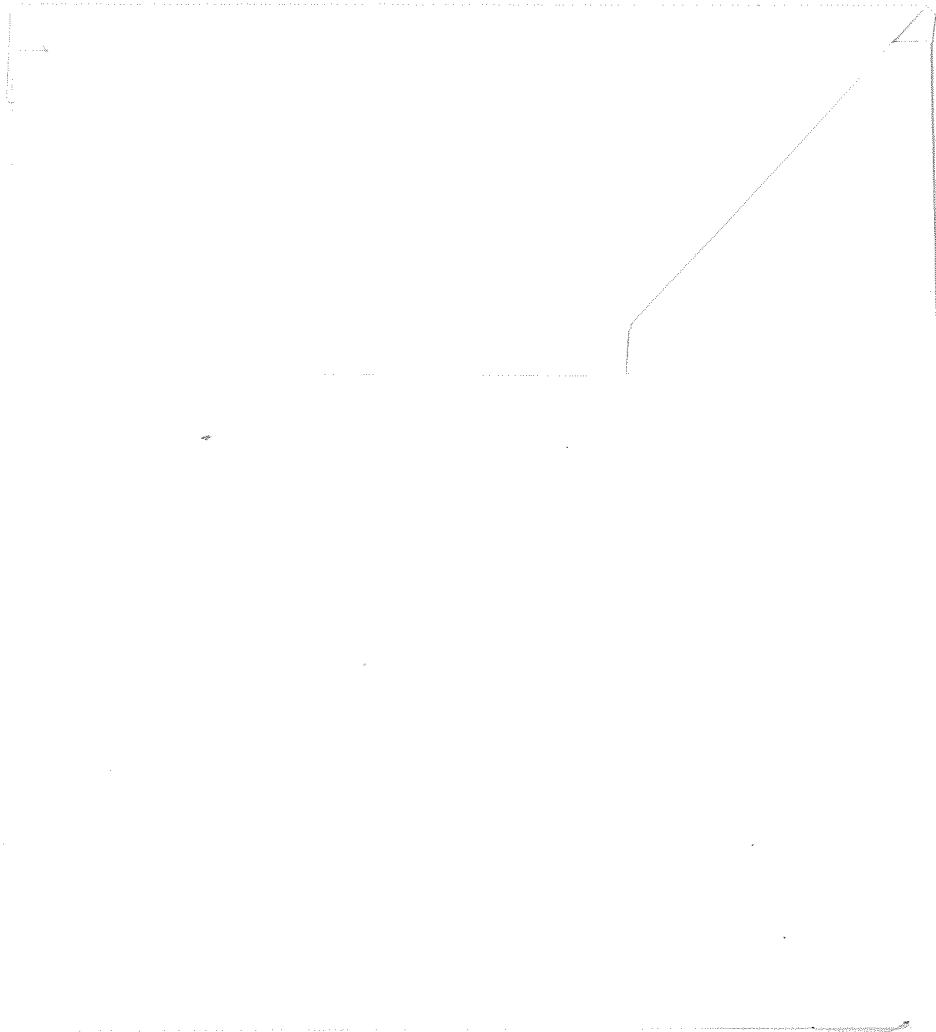
Contents

Abstract.....	ii
Acknowledgments.....	iii
Contents.....	iv
Transient Pressure Animations	vi
List of Figures.....	vii
Notation.....	x
1. Introduction	1-1
1.1 Project Rationale.....	1-1
1.2 Aims of this Research	1-2
1.3 Description of this Thesis	1-2
2. Overview of Vehicle Crosswind Aerodynamics.....	2-3
2.1 Introduction	2-3
2.2 Origin of Vehicle Forces under Transient Crosswinds	2-3
2.3 How Does a Vehicle Respond to a Crosswind?	2-5
2.4 Implications of Future Environmental Legislation	2-6
2.5 Conclusions	2-11
3. Methods to Decrease Crosswind Sensitivity	3-13
3.1 Introduction	3-13
3.2 Experimental Methods of Crosswind Testing	3-13
3.3 Wind Tunnel Test Philosophy and Modeling Technique	3-16
3.4 Assessing an Aerodynamic Design.....	3-17
3.5 Vehicle Aerodynamics.....	3-18
3.6 Conclusions	3-23
4. Experimental Equipment.....	4-27
4.1 Introduction	4-27
4.2 Track Improvements.....	4-29
4.3 Experimental Models.....	4-31
4.4 Data Recording Systems.....	4-32
4.5 Data Reduction	4-33
4.6 Data Accuracy and Repeatability	4-37
4.7 Development of Dynamic Pressure Measurement System	4-39
4.8 Conclusions	4-45
5. Crosswind Aerodynamics of a Flat Plate Model	5-59
5.1 Introduction	5-59
5.2 Results.....	5-59
5.3 Discussion	5-62
5.4 Conclusions	5-64
6. Crosswind Aerodynamics of a Sharp Edged 1-Box Model	6-81
6.1 Introduction	6-81
6.2 Results.....	6-81

6.3	Discussion	6-86
6.4	Conclusions	6-89
7.	Crosswind Aerodynamics of a Radiused Edged 1-Box Model	7-111
7.1	Introduction	7-111
7.2	Results.....	7-111
7.3	Discussion	7-115
7.4	Conclusions	7-118
8.	Crosswind Aerodynamics of a 2-Box Model.....	8-139
8.1	Introduction	8-139
8.2	Results.....	8-139
8.3	Discussion	8-143
8.4	Conclusions	8-144
9.	Crosswind Aerodynamics of a Sports Utility Vehicle.....	9-159
9.1	Introduction	9-159
9.2	Results.....	9-159
9.3	Discussion	9-161
9.4	Conclusions	9-163
10.	Summary and Conclusions	10-173
10.1	Overall Summary of SUV Crosswind Sensitivity.....	10-173
10.2	Development of a Dynamic Pressure Measurement System.....	10-174
10.3	Summary of Test Data	10-174
10.4	Further Work.....	10-176
Appendix A: Comparison of Previously Collected Data.....		179
Differences in Test Technique		179
Appendix B: Equipment Specifications and Calibrations		187
Force and Moment Data.....		187
Pressure Data		187
Appendix C: Program Listings		189
Dynamic Pressure Data Reduction of Radiused 1-Box Model		191
Steady State Pressure Reduction of Radiused 1-Box Model.....		199
Dynamic Force Data Reduction of Radiused 1-Box Model		203
Steady State Force Data Reduction of Radiused 1-Box Model.....		208
Fortran Program to Reduce Pressure Data to Fieldview Format.....		210

Transient Pressure Animations

The CD contains transient pressure animations produced in Fieldview for the flat plate, sharp edged 1-box, radiused edged 1-box and 2-box models. The standard mpeg format animations require Windows 95/NT or later with the latest version of Windows Media Player (also included).



List of Figures

- Figure 2-1 Increased Transient Response of Aerodynamic Yawing Moment. After Kobayashi¹⁴
- Figure 3-1 Different Velocity Profiles to Show Skew
- Figure 3-2 Pressure Map of Rover 800 Saloon. After Howell
- Figure 3-3 Variation of Drag Coefficient with Backlight Angle. After Morel
- Figure 3-4 Formation of Vortices at the Rear of a Vehicle. After Morel
- Figure 3-5 Generation of Leeward Negative Pressure on a Typical Saloon. After Barth
- Figure 4-1 The Crosswind Track Facility and 2.4m x 1.2m Wind Tunnel
- Figure 4-2 Cross section of Crosswind Track Facility
- Figure 4-3 Static Pressure Variation along the Groundboard
- Figure 4-4 Change in Static Pressure against Dynamic Pressure
- Figure 4-5 New Model Carriage Return Mechanism
- Figure 4-6 Modified Model Carriage Return Mechanism
- Figure 4-7 Dynamic Pressure Variations across the Wind Tunnel Working Section
- Figure 4-8 Static Pressure Variations across the Wind Tunnel Working Section
- Figure 4-9 Repeatability of Wind-off Track Signatures (12 Runs)
- Figure 4-10 Flat Plate Model Showing Tapping Positions and Model Supports
- Figure 4-11 Exterior Dimensions and Pressure Tapping Locations of 1-Box Model
- Figure 4-12 Exterior Dimensions and Pressure Tapping Locations of 2-Box Model
- Figure 4-13 Exterior Dimensions and Pressure Tapping Locations of Range Rover Model
- Figure 4-14 Output Signal Pre-processing. After Macklin
- Figure 4-15 Idealised Signal and various Hamming Window Filters
- Figure 4-16 Typical Track Signature Showing Removal of Noise by the Selected Filter
- Figure 4-17 Track Signatures for 30° Yaw Case with Various Lowpass Filter Settings
- Figure 4-18 Removal of Track Signature at Zero Degree Yaw Angle
- Figure 4-19 Schematic of Error in Superpositioning of Track Signatures
- Figure 4-20 Recommended Wall Tapping Geometry. After Benedict
- Figure 4-21 Drift Associated with Sealing Pressure Reference at Atmospheric
- Figure 4-22 Influences of Tapping and Tube Geometry on Pressure Transducer Response
- Figure 4-23 Influence of Tubing Length on Pressure Transducer Response
- Figure 4-24 Experimental Arrangements for Pressure Transducer Frequency Response Test
- Figure 4-25 Amplitude Ratios for Different Lengths (250 – 450mm) of Connecting Tubing
- Figure 4-26 Phase Differences for Different Lengths (250 – 450mm) of Connecting Tubing
- Figure 5-1 Variation of Side Force Coefficient with Yaw Angle for Flat Plate
- Figure 5-2 Variation of Yawing Moment Coefficient with Yaw Angle for Flat Plate
- Figure 5-3 Flat Plate Side Force Coefficient Dynamic Traces, 5 to 25° yaw
- Figure 5-4 Flat Plate Yawing Moment Coefficient Dynamic Traces, 5 to 25° yaw
- Figure 5-5 Flat Plate Side Force Coefficient Dynamic traces Calculated from Integrated Pressure Distributions
- Figure 5-6 Flat Plate Yawing Moment Dynamic traces Calculated from Integrated Pressure Distributions
- Figure 5-7 Mean Dynamic Windward Centre Line Pressures Yaw Angles 0 to 25°, Leading edge to right of page
- Figure 5-8 Mean Dynamic Leeward Centre Line Pressures Yaw Angles 0 to 25°, Leading edge to right of page
- Figure 5-9 Comparison of Mean Dynamic and Steady State Test Windward Centre Line Pressures
- Figure 5-10 Comparison of Mean Dynamic and Steady State Test Leeward Centre Line Pressures
- Figure 5-11 Flat Plate Steady State Pressure Distribution of Windward Face (0-25°) Leading Edge to Right of Page
- Figure 5-12 Flat Plate Steady State Pressure Distribution of Leeward Face (0-25°) Leading Edge to Right of Page
- Figure 5-13 Flat Plate Mean Dynamic Pressure Distribution of Windward Face (0-25°) Leading Edge to Right of Page
- Figure 5-14 Flat Plate Mean Dynamic Pressure Distribution of Leeward Face (0-25°) Leading Edge to Right of Page
- Figure 5-15 Yawing Moment Coefficient Changes on each Face Integrated from Dynamic Pressure Distributions
- Figure 5-16 Side Force Coefficient Changes on each Face Integrated from Dynamic Pressure Distributions
- Figure 5-17 Flat Plate Transient Minimum Peak Pressures for 5 - 25° yaw angle
- Figure 5-18 Positions of Flat Plate Transient Peak Pressures for 5 - 25° yaw angle
- Figure 5-19 Flat Plate Flow Visualisation by Smoke Trace, Yaw Angle 10 - 40°
- Figure 5-20 Stills off Film Taken of Flat Plate Leeward Face Flow Visualisation by Fluorescent Tuft, Yaw Angle 0 - 25°
- Figure 5-21 Generalised Flow Structure of Flat Plate Leeward Face. Leading Edge to Left of Page

Figure 5-22 Schematic Showing Plan View of Model at Gust Exit

Figure 6-1 Variation of Lift Force Coefficient with Yaw Angle for Sharp Edged 1-Box Model

Figure 6-2 Variation of Pitching Moment Coefficient with Yaw Angle for Sharp Edged 1-Box Model

Figure 6-3 Variation of Side Force Coefficient with Yaw Angle for Sharp Edged 1-Box Model

Figure 6-4 Variation of Yawing Moment Coefficient with Yaw Angle for Sharp Edged 1-Box Model

Figure 6-5 Variation of Rolling Moment Coefficient with Yaw Angle for Sharp Edged 1-Box Model

Figure 6-6 Sharp Edged 1-Box Model Lift Force Coefficient Dynamic Traces for Various Yaw Angles

Figure 6-7 Sharp Edged 1-Box Model Pitching Moment Coefficient Dynamic Traces for Various Yaw Angles

Figure 6-8 Sharp Edged 1-Box Model Side Force Coefficient Dynamic Traces for Various Yaw Angles

Figure 6-9 Sharp Edged 1-Box Model Yawing Moment Coefficient Dynamic Traces for Various Yaw Angles

Figure 6-10 Sharp Edged 1-Box Model Rolling Moment Coefficient Dynamic Traces for Various Yaw Angles

Figure 6-11 Sharp Edged 1-Box Model Steady State Pressure Map at 0° Yaw. Leading Edge to Left of Page

Figure 6-12 Sharp Edged 1-Box Model Steady State Pressure Map at 5° Yaw. Leading Edge to Left of Page

Figure 6-13 Sharp Edged 1-Box Model Steady State Pressure Map at 10° Yaw. Leading Edge to Left of Page

Figure 6-14 Sharp Edged 1-Box Model Steady State Pressure Map at 15° Yaw. Leading Edge to Left of Page

Figure 6-15 Sharp Edged 1-Box Model Steady State Pressure Map at 20° Yaw. Leading Edge to Left of Page

Figure 6-16 Sharp Edged 1-Box Model Steady State Pressure Map at 25° Yaw. Leading Edge to Left of Page

Figure 6-17 Sharp Edged 1-Box Model Mean Dynamic Pressure Map at 10° Yaw. Leading Edge to Left of Page

Figure 6-18 Sharp Edged 1-Box Model Mean Dynamic Pressure Map at 20° Yaw. Leading Edge to Left of Page

Figure 6-19 Changes in Sharp Edged 1-Box Model Yawing Moment Calculated from Dynamic Pressures

Figure 6-20 Changes in Sharp Edged 1-Box Model Side Force Calculated from Dynamic Pressures

Figure 6-21 Positions of Transient Peak Pressures on Leeward Face for Dynamic Pressure Tests

Figure 6-22 Sharp Edged 1-Box Model Transient Peak Pressures on Leeward Face for Dynamic Pressure Tests

Figure 6-23 Sharp Edged 1-Box Model Surface Paint Flow Visualisation at 0° yaw

Figure 6-24 Sharp Edged 1-Box Model Surface Paint Flow Visualisation at 10° yaw

Figure 6-25 Sharp Edged 1-Box Model Surface Paint Flow Visualisation at 20° yaw

Figure 6-26 Sharp Edged 1-Box Model Flow Visualisation by Fluorescent Tuft 0 - 25° yaw

Figure 6-27 Reynolds Sensitivity for Sharp Edged 1-Box Model at 5° Yaw Angle

Figure 6-28 Comparison of Reynolds Sensitivity for Sharp Edged 1-Box Model

Figure 7-1 Variation of Lift Force Coefficient with Yaw Angle for Radiused Edged 1-Box Model

Figure 7-2 Variation of Pitching Moment Coefficient with Yaw Angle for Radiused Edged 1-Box Model

Figure 7-3 Variation of Side Force Coefficient with Yaw Angle for Radiused Edged 1-Box Model

Figure 7-4 Variation of Yawing Moment Coefficient with Yaw Angle for Radiused Edged 1-Box Model

Figure 7-5 Variation of Rolling Moment Coefficient with Yaw Angle for Radiused Edged 1-Box Model

Figure 7-6 Radiused Edged 1-Box Model Lift Force Coefficient Dynamic Traces for 5 - 25° Yaw Angle

Figure 7-7 Radiused Edged 1-Box Model Side Force Coefficient Dynamic Traces for 5 - 25° Yaw Angle

Figure 7-8 Radiused Edged 1-Box Model Yawing Moment Coefficient Dynamic Traces for 5 - 25° Yaw Angle

Figure 7-9 Radiused Edged 1-Box Model Rolling Moment Coefficient Dynamic Traces for 5 - 25° Yaw Angle

Figure 7-10 Radiused Edged 1-Box Model Steady State Pressure Map at 0° Yaw Angle

Figure 7-11 Radiused Edged 1-Box Model Steady State Pressure Map at 5° Yaw Angle

Figure 7-12 Radiused Edged 1-Box Model Steady State Pressure Map at 10° Yaw Angle

Figure 7-13 Radiused Edged 1-Box Model Steady State Pressure Map at 15° Yaw Angle

Figure 7-14 Radiused Edged 1-Box Model Steady State Pressure Map at 20° Yaw Angle

Figure 7-15 Radiused Edged 1-Box Model Steady State Pressure Map at 25° Yaw Angle

Figure 7-16 Radiused Edged 1-Box Model Mean Dynamic Pressure Map at 10° Yaw Angle

Figure 7-17 Radiused Edged 1-Box Model Mean Dynamic Pressure Map at 20° Yaw Angle

Figure 7-18 Changes in Radiused Edged 1-Box Model Moment Coefficients Calculated from Dynamic Pressure Tests

Figure 7-19 Changes in Radiused Edged 1-Box Model Force Coefficients Calculated from Dynamic Pressure Tests

Figure 7-20 Position of Radiused Edged 1-Box Model Transient Peak Pressures on Leeward Face

Figure 7-21 Position of Transient Peak Pressures on Leeward Face for Radiused Edged 1-Box Model

Figure 7-22 Radiused Edged 1-Box Model Flow Visualisation by Surface Paint at 0° Yaw Angle

Figure 7-23 Radiused Edged 1-Box Model Flow Visualisation by Surface Paint at 10° Yaw Angle

Figure 7-24 Radiused Edged 1-Box Model Flow Visualisation by Surface paint at 20° Yaw Angle

Figure 7-25 Radiused Edged 1-Box Model Flow Visualisation by Fluorescent Tuft 0 - 25° Yaw Angle

Figure 7-26 Reynolds Sensitivity for Radiused Edged 1-Box Model at 5° yaw angle

Figure 7-27 Comparison of Reynolds Sensitivity for Radiused Edged 1-Box Model

Figure 8-1 Variation of Lift Force Coefficient with Yaw Angle for 2-Box Model

Figure 8-2 Variation of Side Force Coefficient with Yaw Angle for 2-Box Model

Figure 8-3 Variation of Yawing Moment Coefficient with Yaw Angle for 2-Box Model

Figure 8-4 Variation of Rolling Moment Coefficient with Yaw Angle for 2-Box Model

Figure 8-5 2-Box Model Lift Force Coefficient Dynamic Traces for 5 - 25° Yaw Angle

Figure 8-6 2-Box Model Side Force Coefficient Dynamic Traces for 5 - 25° Yaw Angle

Figure 8-7 2-Box Model Yawing Moment Coefficient Dynamic Traces for 5 - 25° Yaw Angle

Figure 8-8 2-Box Model Rolling Moment Coefficient Dynamic Traces for 5 - 25° Yaw Angle

Figure 8-9 Steady State 2-Box Pressure Contour Map at 0° Yaw Angle. Leeward Face at Top of Page

Figure 8-10 Steady State 2-Box Pressure Contour Map at 5° Yaw. Leeward Face at Top of Page

Figure 8-11 Steady State 2-Box Pressure Contour Map at 10° Yaw. Leeward Face at Top of Page

Figure 8-12 Steady State 2-Box Pressure Contour Map at 15° Yaw. Leeward Face at Top of Page

Figure 8-13 Steady State 2-Box Pressure Contour Map at 20° Yaw. Leeward Face at Top of Page

Figure 8-14 Steady State 2-Box Pressure Contour Map at 25° Yaw. Leeward Face at Top of Page

Figure 8-15 Mean Dynamic 2-Box Pressure Contour Map at 10° Yaw. Leeward Face at Top of Page

Figure 8-16 Mean Dynamic 2-Box Pressure Contour Map at 20° Yaw. Leeward Face at Top of Page

Figure 8-17 Changes in Pressure Coefficient along the A-Pillar

Figure 9-1 Variation of Lift Force Coefficient with Yaw Angle for Range Rover Model

Figure 9-2 Variation of Side Force Coefficient with Yaw Angle for Range Rover Model

Figure 9-3 Variation of Yawing Moment Coefficient with Yaw Angle for Range Rover Model

Figure 9-4 Variation of Rolling Moment Coefficient with Yaw Angle for Range Rover Model

Figure 9-5 Range Rover Model Lift Force Coefficient Dynamic traces for 5 - 25° Yaw Angle

Figure 9-6 Range Rover Model Side Force Coefficient Dynamic traces for 5 - 25° Yaw Angle

Figure 9-7 Range Rover Model Yawing Moment Coefficient Dynamic traces for 5 - 25° Yaw Angle

Figure 9-8 Range Rover Model Rolling Moment Coefficient Dynamic traces for 5 - 25° Yaw Angle

Figure 9-9 Range Rover Model Steady State Pressures 0 - 25° Yaw

Figure 9-10 Range Rover Model Steady State Pressures, Tapping No. 1-10

Figure 9-11 Range Rover Model Dynamic Pressures at 24° yaw, Tapping No. 1-10

Figure 9-12 Comparison of Mean Dynamic and Steady State Pressure Coefficients

Figure 9-13 Comparison of Lift Force Coefficient for all Models

Figure 9-14 Comparison of Side Force Coefficient for all Models

Figure 9-15 Comparison of Yawing Moment Coefficient for all Models

Figure 9-16 Comparison of Rolling Moment Coefficient for all Models

Figure A-1 Repeatability within a Dataset

Figure A-2 Comparison of Rear lift Coefficient for Passenger car Model

Figure A-3 Comparison of Front Lift Coefficient for Passenger car Model

Figure A-4 Comparison of Rear Lift Coefficient for Passenger car Model

Figure A-5 Comparison of Side Force Coefficient for Passenger car Model

Figure A-6 Comparison of Yawing Moment Coefficient for Passenger car Model

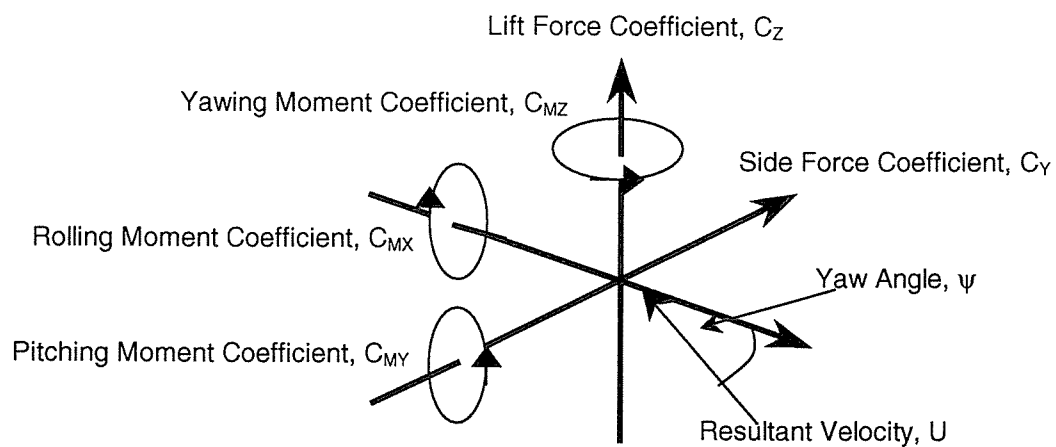
Figure A-7 Comparison of Rolling Moment Coefficient for Passenger car Model

Figure B-1 Typical Balance Calibration

Figure B-2 Typical Sensor Technics SLP010DD4 Pressure Calibration

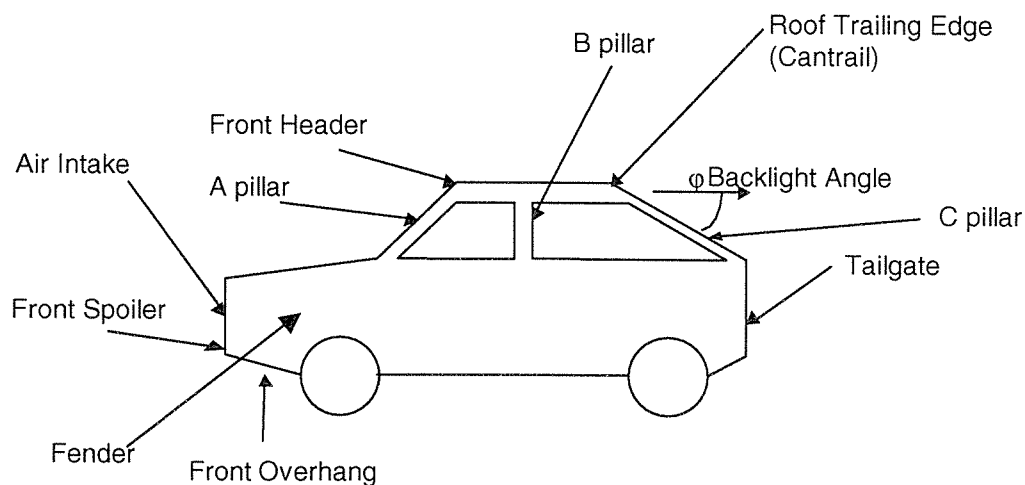
Notation

A_F Model frontal area (m^2)	q_c Corrected Freestream dynamic pressure (Pa)
A_S Model side area (m^2)	r model radii (mm)
C Wind tunnel sectional area (m^2)	Re Reynolds number = $\rho U w / \mu$
C_F Force coefficient	S Duplex model area (m^2)
C_Z Lift force coefficient	U_M Model Velocity (m/s)
C_M Moment coefficient	U_W Wind Tunnel Velocity (m/s)
C_{MZ} Yawing moment coefficient	U Resultant of Model and Wind Velocity (m/s)
C_P Pressure coefficient	W Gust width (m)
C_{MY} Pitching moment coefficient	w Model Width (m)
C_{MX} Rolling moment coefficient	x Characteristic dimension
C_Y Side force coefficient	x Distance across wind tunnel working section (m)
C_{MZ} Yawing moment coefficient	y Characteristic dimension
F Force (N)	z Characteristic dimension
h Model height (m)	β Backlight angle (deg.)
h_g Model ground clearance (m)	ρ Density of air (kg/m^3)
l Model length (m)	μ Dynamic viscosity ($kg/m/s$)
M Moment (Nm)	ψ Yaw angle (deg.)
P Total Pressure (Pa)	
q Dynamic pressure (Pa)	
q_∞ Freestream static pressure (Pa)	



The axis system for the force and moment coefficients is the centre axes of the models, a positive side force occurs with a positive wind loading and a positive yawing moment is when the nose of the model turns leeward. To comply with the general convention, the rolling moment is translated to the groundplane but because drag is not measured pitching moment is calculated about the model central axes.

Glossary of Vehicle Terms



Abbreviations

ABL – Atmospheric Boundary Layer

CFD – Computational Fluid Dynamics

JSAE – Japanese Society of Automotive Engineers

JWEIA – Journal of Wind Engineering and Industrial Aerodynamics

MPEG – Motion Pictures Experts Group

mpg – miles per gallon

MPV – Multi Purpose Vehicle

SAE – Society of Automotive Engineers

SUV – Sports Utility Vehicle

WES – Wind Engineering Society

1. Introduction

1.1 Project Rationale

Transient crosswinds have a detrimental effect on the ride and handling of road vehicles whereby passenger comfort is degraded and drivers experience fatigue. More seriously, extreme crosswinds can cause critical course deviations leading to vehicle collisions and even overturning.

In recent years, the sports utility vehicle (SUV) has seen an increased share of the passenger vehicle market mainly due to its rugged masculine appeal and the provision of secure transportation of occupants. Buyers of the SUV are happy with the idea that the vehicle could go off-road if needed but it is primarily used in the urban environment. The perception of off-road qualities has meant that SUV's have bluff sharp-lined body features and the appearance of a solid build quality. Consequently SUV's are neither styled aerodynamically to any great extent (used in this context as meaning to reduce the drag coefficient) and the sturdy appearance has come with an increased size and weight over the conventional passenger vehicle. This is seen as an advantage with respect to crosswind stability but even so, SUV's are reported to be particularly sensitive to crosswind disturbances¹. Proposed legislation to limit the carbon dioxide emissions of vehicles will enforce a reduction of aerodynamic drag and weight, both of which have previously been shown to increase crosswind sensitivity². The advantage of increased weight and bluff bodied styling will then have been lost and the crosswind sensitivity of SUV's could be degraded still further.

This research program is primarily motivated by a need to determine the transient crosswind characteristics of sports utility vehicles. The aerodynamic response of vehicles to a crosswind disturbance is conventionally determined by analysis of aerodynamic force and moment data recorded during wind tunnel tests. This does not reveal the contributions of each body element to the overall aerodynamic forces that can only be achieved by surface pressure measurements. Previous research³ has also shown that conventional steady state wind tunnel testing does not adequately model the transient nature of crosswinds.

A series of tests on simple geometric shapes of aspect ratios similar to those of typical SUV's have been performed using the Cranfield crosswind track facility that simulates a crosswind gust. Scale models have been tested in order of increasing shape complexity to gain an understanding of the complex time dependent and separated flow fields around bluff vehicles when subjected to a transient crosswind gust. Pressure mapping of the model surfaces has been

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1. Howell J P, Experimental Results From a Small SUV Tested in the MIRA Crosswind Generator, Unpublished Report, Rover Group UK
 2. Emmelmann H, Chapter 3 'Driving Stability in Side Winds' in Aerodynamics of Road Vehicles, (ed. Hucho W), 1987 Butterworths
 3. Macklin A R, Measuring the Effects of Crosswinds on Cars, Ph.D. Thesis, Cranfield University, 1996

performed to reveal transient aspects of the fluid flow that are not shown in conventional force measurement.

1.2 Aims of this Research

The principle aims of this research were:

1. Assess the present day crosswind sensitivity of sports utility vehicles
2. Develop a pressure measurement system for use under the dynamic test conditions of the Cranfield crosswind track test facility
3. Conduct a series of tests on simple geometric shapes resembling the aspect ratios of SUV's to correlate aerodynamic force and pressure data and gain a greater understanding of SUV aerodynamics under transient crosswind conditions

1.3 Description of this Thesis

Chapter 2 presents an overview of the current position of crosswind aerodynamics and the response of a vehicle in a crosswind. The origin of aerodynamic forces and moments in a transient crosswind are described and some commonly used terms and notation are defined. The implications of environmental legislation to reduce emissions of vehicular carbon dioxide is then discussed and it is concluded that such legislation will have a detrimental effect on crosswind sensitivity. Chapter 3 then considers the techniques available to the aerodynamic designer to reduce the sensitivity of a vehicle in a crosswind. It is concluded that to satisfactorily determine the aerodynamic response of a vehicle in a crosswind a moving model and simulated crosswind gust is required. Results from previous aerodynamic tests are presented and the influence of specific shape changes on the response of a vehicle in a transient crosswind is discussed. The chapter concludes that the present techniques are still based on an empirical approach and in light of an anticipated increase in crosswind sensitivity will not be sufficient to describe the aerodynamic response to transient crosswinds. A detailed understanding of the fluid dynamics around the vehicle is required and this can only be provided by measurement of surface pressures.

Chapter 4 describes the Cranfield Crosswind Track Test Facility and experimental arrangement. Improvements to the facility in order to improve data repeatability are described and the data reduction process is detailed. The recording of pressures under the dynamic testing conditions of the crosswind track is original work and the development and calibration of pressure equipment is also presented in this chapter. Chapter's 5 to 9 present results and discussions of steady state and transient aerodynamic data of the various models tested during this research. They are listed in order of increasing shape complexity: – flat plate (chapter 5), sharp edged 1-box model (chapter 6), radiused edged 1-box model (chapter 7), 2-box model (chapter 8) and Range Rover model (chapter 9).

Chapter 10 contains a summary of the research and overall conclusions.

2. Overview of Vehicle Crosswind Aerodynamics

2.1 Introduction

This chapter defines the origin of crosswind forces and describes how a vehicle responds to a crosswind. Commonly used terms used in crosswind aerodynamics are defined and the implication of future legislation to reduce vehicular carbon dioxide emissions is then discussed.

2.2 Origin of Vehicle Forces under Transient Crosswinds

Crosswind gusts flowing around a moving vehicle cause differences in pressure between the windward and leeward faces resulting in aerodynamic forces that then must be balanced by the tyre grip of the car on the road. Forces (drag, lift and side force) generated in the three planes act through a point known as the centre of pressure. They can then be resolved about a body reference point and additional moments (pitch, yaw and roll) are generated. The vectors of aerodynamic forces and centre of pressure are solely a function of aerodynamic shape, but the magnitude of moments are also dependent upon the position of the neutral steer point, which is determined by:

- Vehicle dynamic properties e.g. steering, suspension, wheelbase length
- Position of centre of mass
- Tyre performance

A number of researchers ^(4,5) have found that vehicle dynamic properties, tyres and mass of a vehicle have a much more pronounced affect on vehicle crosswind stability than that caused by different aerodynamics. Howell⁶ also found the vehicle yaw rate to increase approximately inversely with tyre stiffness, wheelbase and vehicle mass, and directly with aerodynamic yawing moment. However, it is concluded that since vehicle class determines the neutral steer point it remains for the aerodynamic yawing moment to be optimised for improved crosswind stability.

Aerodynamic yawing moment is, to some degree, also dependent on vehicle class but there is much scope for improving yawing moment by changing body details. The overall vehicle shape can be classed as one, two or three box forms. A typical example of a 3-box shape is a saloon, 2-box an estate or SUV and 1-box a MPV, and it is the latter 2 configurations that this project is

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4. Buheim R, Marezke J and Piatek R, The Control of Aerodynamic Parameters Influencing Vehicle Dynamics, SAE 850279, 1985
 5. Macadam C C, Sayes M W, Pointer J D and Gleason M, Crosswind Sensitivity of Passenger Cars and the Influence of Chassis and Aerodynamic Properties on Driver Preferences, Vehicle System Dynamics, vol. 19, pp. 201-236, 1990
 6. Howell J P, Shape Features Which Influence Crosswind Sensitivity, IMechE Vehicle Ride and Handling, C466/036, pp. 43-52, 1993

specifically concerned with. A full-scale test⁷ of 5 different vehicles using a crosswind generator showed that 1-box shaped vehicles are extremely sensitive to crosswinds compared to passenger cars. Experimental results from testing a sports utility vehicle in a crosswind generator also showed higher yaw rates and lateral deviation than measured on conventional passenger cars. Takada⁸ also noticed from steady state wind tunnel tests that the aerodynamic coefficients of 1-box vehicles are two or three times larger than conventional passenger vehicles. The increase in crosswind sensitivity between 2 and 1-box type vehicles and conventional passenger vehicles is mainly due to their relatively large side area. For SUV's, there is also a large ground clearance and therefore higher roofline which increases the aerodynamic rolling moment. The stability of SUV's is partly compensated because they are designed as an off-road vehicle, which requires a sturdy design, and consequently are relatively massive. Specific shape changes that influence the aerodynamic response of the overall vehicle shape such as radiusing of edges and streamlining are detailed in chapter 3.

Driver participation (termed closed loop testing) is an important component of actual crosswind behavior. The reaction of the driver to a crosswind disturbance can cause differing lateral deviations compared to the fixed steering wheel case (open loop) due to exaggerated reactions by different drivers. Kramer⁹ points out that neglecting driver participation is not very relevant for actual crosswind behavior and has shown that the comparison between open loop wind tunnel tests and crosswind aerodynamic data in real car testing is very poor. Macadam⁵ specifically addresses crosswind sensitivity from the perspective of the driver and develops a dynamic crosswind model to analyse the crosswind sensitivity of the driver-vehicle system. The influence and interaction of chassis characteristics and aerodynamic properties on driver preferences are then linked to the vehicle system response measured during full-scale tests. It was found that the position of the centre of pressure is a good initial indicator of a vehicles crosswind sensitivity as perceived by the driver, but the position of centre of mass and roll compliance (as determined by suspension characteristics) also clearly influenced driver evaluations. The lowest subjective rating was with a forward centre of pressure, rearward centre of mass and increased roll compliance.

It is evident from the above examples that closed loop testing is essential to assess a vehicle's overall crosswind response but when considering aerodynamics alone it must be considered that not all drivers are the same and it is an extra variable to monitor in an already complicated problem⁴. Jacobson¹⁰

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7. Klein R H and Hogue J R, Effects of Crosswinds on Vehicle Response - Full Scale Tests and Analytical Predictions, SAE 800848, 1980
 8. Takada H, Nakagawa K and Shinoda H, Crosswind Stability of 1-Box Car, JSAE Review Vol. 11, No. 1, pp. 30-37, 1990
 9. Kramer C, Grundmann R and Gerhardt H J, Testing of Road Vehicle under Crosswind Conditions, JWEIA vol. 38, pp. 59-69, 1991
 10. Jacobson M A, Accident Avoidance - Crosswind Sensitivity of some Streamlined Cars, 10th International Technical Conference on Safety Vehicles, Oxford, July 1995

agrees and points out that there is little chance of improving driver skill and therefore it is up to the car manufacturers to produce vehicles fit for anyone to drive regardless of ability or experience.

2.3 How Does a Vehicle Respond to a Crosswind?

It has often been written in the automotive press that crosswinds of sufficient magnitude can have detrimental effects on the ride and handling of a vehicle. Ride is an ambiguous term and can have several different meanings depending on the nature of the external forces. In straight line driving in the absence of a crosswind, a vehicle's ride is measured by its cornering performance and straight line driving stability. In the context of crosswind forces ride can also be termed crosswind sensitivity and is often a subjective assessment made by the driver (or passenger) on the performance of the vehicle. According to industry¹¹, foremost in this assessment is vehicle refinement, which includes general passenger comfort, aerodynamic noise and handling criteria such as the frequency and amount of effort required correcting a course deviation. Baker¹² assessed vehicle crosswind response from the viewpoint of vehicle safety and identifies 3 types of instability that could lead to accidents due to crosswinds:

- Overturning
- Sideslip
- Rotational

The first instability is more applicable to trains and high-sided vehicles rather than passenger vehicles and will not be considered here. Sideslip occurs due to the frictional forces provided by the vehicle tyre reactions being overcome by a side wind force. This is unlikely since the side force on a typical passenger vehicle would have to be considerable to induce sideslip. Therefore rotational instability, defined by Baker¹² as excessive aerodynamic yawing moment to cause critical course deviation, is the sole concern of passenger vehicle safety. SUV's have previously been reported to exhibit excessive course deviations¹ when subjected to crosswinds, although tests were conducted without driver participation and in the real world the driver acts to compensate course deviations. This aside, the wind velocities required to produce such a vehicle response are of a rare occurrence and therefore it remains for vehicle refinement to be the main concern of crosswind sensitivity.

There are several reasons why the crosswind sensitivity of vehicles is of immediate interest. The first of these is that in improving our communication network more exposed motorways and embankments that cause local wind acceleration have been constructed. Howell⁶ has identified the following vehicle responses at motorway cruising speeds when subjected to crosswinds:

11. Private communication, Jeff Howell, Manager Aerodynamics, Rover Group, March 1997

12. Baker C J, A Simplified Analysis of Various Types of Wind-Induced Road Vehicle Accidents, JWEIA vol. 22, pp69-85, 1986

Cross Wind Speed	Vehicle Response
<2.5m/s	Wander
10m/s	Buffeting, steering corrections required, poor ride quality
>15m/s	Possibility of vehicle being pushed out of lane

Narita¹³ has shown that topographical features can significantly worsen the properties of the natural wind with respect to crosswind sensitivity. Given that the extension of the road network is set to continue and expand into more exposed areas in the future then we can expect increased crosswind instabilities.

There are two states to consider when looking at the crosswind sensitivity of vehicles: the steady state and transient response. As the term implies, the steady state response yields aerodynamic forces and moments that are constant apart from fluctuations due to turbulence of the natural wind. Transient conditions are experienced by a vehicle when it passes into the natural wind and typically occur at bridge abutments or when passing a high sided vehicle. Vehicular aerodynamic response is altered by transient conditions. For example, Kobayashi¹⁴ found that the aerodynamic yawing moment peaks 1.3 body lengths after entrance to a transient crosswind and then settles to a steady value of approximately half the peak value after 4 body lengths (Figure 2-1). Macklin³ shows agreement with this evidence but Klein⁷ found that no significant differences were found between steady state and transient crosswinds for a wide range of vehicle shapes. This contradiction in results is most probably due to differences in test technique and is discussed further in chapter 3.

Howell⁶ points out that improvements, although indirectly, have been made to reduce the susceptibility of vehicles to crosswinds. Firstly, the increase in front wheel drive vehicles in recent years has led to a better weight distribution as far as crosswind stability is concerned. This is because the neutral steer point has moved towards the front axle and the aerodynamic yawing moment acting around this point is consequently reduced. Secondly, the car under much public pressure has recently become safety conscious and green. The technological advancements that accompany this change in attitude such as side impact bars and catalytic converters have raised the overall mass of a vehicle. This increase in tyre reactions combined with improved tyre technologies has helped to reduce the possibility of crosswind instabilities that would cause excessive course deviations.

2.4 Implications of Future Environmental Legislation

The future environmental effects that will now be described were first realised at the Earth Summit held at Rio de Janeiro, Brazil in June 1990. This summit

13. Narita N and Katsuragi M, Gust Wind Effects on Driving Safety of Road Vehicles, JWEIA, vol. 9 1981, pp. 181-191

14. Kobayashi N and Yamada M, Stability of a One Box Type Vehicle in a Crosswind - An Analysis of Transient Aerodynamic Forces and Moments, SAE 881878, 1988

revealed the importance of climate change upon the globe and the need for urgent action. As a result, 150 countries (and more since) signed the Framework Convention on Climate Change that set targets to reduce greenhouse gas emissions. For countries in Europe and other industrialised nations this originally meant reducing emissions of greenhouse gases to 1990 levels by the year 2000. Since the Rio summit there have been subsequent environmental conferences, the latest in Kyoto, Japan in December 1997. Though heavily disputed by the industrialised nations, a revised and legally binding agreement to reduce greenhouse gas emissions was eventually set¹⁵. The *European Union* (EU) agreed to reduce its emissions by 8% from 1990 levels by the period 2008 - 2012 and also to continue its commitments to the original Rio summit. Germany, the largest producer of greenhouse gas emissions in the EU is committed to 21% of this total reduction and Great Britain to 13% but some European nations will have no reductions and some will even increase.

The greenhouse gases of which carbon dioxide (CO₂) is the greatest contributor come together as a layer around the globe in the upper atmosphere. This layer stops the release of infra red radiation emitted by the earth's surface and thereby raises the mean global temperature. A report¹⁶ by the Intergovernmental Panel on Climate Change that represented views of over 300 of the worlds leading scientists on the matter concluded:

- The concentration of greenhouse gases in the atmosphere has increased substantially as a result of human activity. This is expected to enhance the natural greenhouse effect.
- Average global temperatures have increased by 0.3 - 0.6⁰C during the last century. This is consistent with models of the enhanced greenhouse effect that would be expected.
- without action, an increase in global average temperatures of 0.3⁰C per decade can be expected. This could cause a sea level rise of around 60mm per decade.

For the UK, the transport sector was responsible for 24% of the total CO₂ production in 1990¹⁷ of which 86% was due to cars and light vans. At the same time, the transport sector has become the fastest growing source of UK CO₂ emissions. In the period 1970 to 1990 the fuel consumption of cars rose by around 70%, car ownership doubled and car mileage increased by 117%. In Europe as a whole, passenger car traffic accounts for around 12% of total man-made CO₂ emissions and road transport CO₂ emissions grew by around 9% from 1990 to 1997¹⁸.

15. Climate Change – Towards an EU Post-Kyoto Strategy, http://europa.eu.int/comm/dg11/docum/98353_en.pdf, (Accessed August 1999)

16. Intergovernmental Panel on Climate Change First Assessment Report, Cambridge University Press 1990 ISBN 0-52-140720-6

17. Climate Change: The UK Program, HMSO January 1994

Since the production of CO₂ by road transport is second only to that of power stations, it is not surprising that the reduction of road transport CO₂ comprises 25% of the total improvement needed in CO₂ emissions. Since the Kyoto summit, all European car manufacturers are committed to the *European Automobile Manufacturers Association* (ACEA) and its agreement with the EEC¹⁸, which states:

- new cars sold in the *European Union* (EU) are to achieve an average CO₂ emission figure of 140 g/km by 2008, this represents a 25% reduction from 1997 levels
- individual car models with CO₂ emissions of 120 g/km or less are to be introduced by 2000

Japanese carmakers have also agreed to the EU proposal for cutting carbon dioxide emissions from automotive exhausts¹⁹. The Japanese Automobile Manufacturers Association (JAMA) will bring emissions down 30 percent from levels allowed in 1995 (ACEA target is 15 percent from 1995 levels by 2008) which will adhere to the EU reduction target of 140 grams of CO₂ per kilometer by 2009. JAMA has a more stringent condition than ACEA because CO₂ emissions from Japanese vehicles sold in Europe are higher than European models because the Japanese vehicles are generally larger.

The methods that have been agreed upon by ACEA and the EEC to reduce CO₂ emissions from road transport are threefold:

- Improving fuel efficiency by new vehicle technologies
- Provide financial incentives to encourage motorists to use more fuel efficient vehicles
- Increased public awareness of the importance of fuel economy

Financial incentives are already being put into place. For example in the UK, vehicle taxation for vehicles with engines less than 1100cc is now two-thirds the cost of those above 1100cc.

In devising and implementing new vehicle technologies, there are three ways for car manufacturers to improve the fuel efficiency of petrol driven vehicles:

1. Improve engine efficiency
2. Reduce the overall mass of the vehicle
3. Reduce the resistive forces to motion.

The detailed analysis into the improvements possible in engine design and the efficiency of the motor engine is beyond the scope of this review. It is sufficient to say that improvements are being made; Volkswagens revolutionary ecomatic engine has been found to cut traffic emissions (CO₂) by 22% and VW engineers

18. CO₂ emissions from cars - The EU Implementing the Kyoto Protocol,
<http://europa.eu.int/comm/dg11/climat/acea.pdf>, (Accessed August 1999)

19. Global Warming Today, Japanese Automakers agree to CO₂ Cuts, September 15 1999

are confident that technical improvements can improve the efficiency of the petrol driven engine by 25%²⁰. Ford²¹ has also recently invested in an environmental testing facility to monitor engine efficiency and is testament to the vehicle manufacturers commitment in this field.

Advanced production techniques for lighter materials than steel (e.g. aluminium) mean that the reduction of the overall weight of a motor vehicle is already possible. An example is the aluminium bodied Audi A8²² which until recently would have been difficult to manufacture using existing methods. The advantages of aluminium as an automotive material are considerable. It is the most abundant metal in the earth's crust, easily recyclable, machinable and is one-third the density and of higher strength than steel. The application of aluminium to the A8 has meant a 40% reduction in weight compared to an equivalent car in steel. Since a 10% reduction in mass yields a 2.5% decrease in CO₂²², there are potentially large rewards for manufacturers investigating in this technology. Aluminium cars have not been seen up till now because it is incompatible with large-scale production. However, after a comprehensive research program Audi engineers claim that with large volumes the same degree of automation as with conventional steel vehicles is now possible²².

VW have also made a dramatic venture investing hundreds of millions of dollars in lighter than steel technology²⁰. Magnesium, which equals aluminium in strength but is only half the mass, will be used in the manufacture of bodywork panels. Magnesium alloys have an extra weight saving of 34% over aluminium and is an excellent material for casting and so compatible with large-scale production.

The Partnership for a New Generation of Vehicles (PNGV) in the United States also sees material development as the focal point of reaching its target of an 80-mpg saloon in production by 2004²⁰. A conceptual channel body structure in stainless steel can potentially provide greater stiffness than present construction techniques and also results in a 40-50% reduction in body mass.

From the above examples, it is apparent that motor manufactures consider mass reduction to be very important in improving fuel efficiency and that it is an area of research attracting large investment. The implication of this reduced mass is that the crosswind sensitivity of passenger vehicles will be increased. SUV's that rely on their mass to counteract crosswind instabilities will be particularly affected. Apart from tyre grip and suspension characteristics, the mass of a vehicle is essentially what keeps it in contact with the road. Simple mechanics tells us that a reduction in mass would decrease tyre reactions and make a vehicle more susceptible to course deviations.

The third method that could be employed by car manufacturers to increase the fuel efficiency of vehicles is by reducing the resistive forces to motion. The resistive forces comprise of tyre rolling resistance and aerodynamic drag but

20. Author Unknown, Benefits of Weight Reduction, Automotive Engineer, vol. 21 No. 6 December 1996

21. Ford UK opens 80 mln stg eco-testing site, Reuters news service, September 27, 1999

22. Birch S, Aluminium Space Frame Technology, Automotive Engineering, January 1994

aerodynamic effects are the more dominant of the two. For a typical passenger car aerodynamic drag composes 70% of the total resistance of a car at 100km/h²³ and for 4x4 vehicles aerodynamic drag becomes dominant at even lower speeds²⁴. The aerodynamic drag of a car is defined as:

$$\text{Drag, } D = \frac{1}{2}\rho V^2 C_D A \quad (1)$$

For a constant air density and velocity, the drag is directly proportional to the drag coefficient C_D and the frontal area A . The frontal area is effectively defined by the vehicle class and so the drag coefficient or vehicle shape will have the greatest influence on reducing drag. It is possible that by improving the vehicle shape and detail optimisation, the drag coefficient could be reduced by 20 - 50% from an average C_D of 0.4 in the early 1980's²³. Since a 10% reduction in the aerodynamic drag has yielded a 3% improvement in fuel consumption for the Euromix Driving Cycle²⁴, this will yield a fuel saving of the order of 6 - 15%. A study of improving fuel consumption by a reduction in weight over improved aerodynamics showed that weight reduction cannot compare to this fuel saving²⁵. Already drag coefficients of 0.3 for mass produced cars are now quite common and in striving to improve fuel efficiency future styling will decrease this figure further. Hucho²³ states that drag coefficients of the order of 0.2 are possible on standard production cars and experimental vehicles have already achieved this figure. An example is the CNR (Italian National Research Council) prototype vehicle that achieved a drag coefficient of 0.196 over twenty years ago²⁶. Clarification of an improving drag coefficient is provided in a report by the Society of Automotive Engineers²⁷. The report shows that for typical passenger vehicles the drag coefficient has been reduced to a minimum of around 0.27 by the 1990's compared to a minimum of 0.36 during the 1980's.

The evidence above shows that the aerodynamic drag coefficient has improved greatly over the past twenty years and that future legislation to govern CO₂ emissions will provide the impetus to reduce the drag coefficient even further. The implication of this reduced drag coefficient is that vehicles will have increased crosswind sensitivity. Howell⁶, Sumitani²⁸ and Emmelmann² have noted that the reduction in the drag coefficient has often resulted in an increase in the aerodynamic yawing moment. An example is when corners are shaped to prevent fluid separation and so improve the drag coefficient. This conflicts with reducing the yawing moment since the separation of the boundary layer is beneficial because it decreases the negative (suction) pressure at the leeward side. The specific shape changes that influence changes in aerodynamic coefficients are detailed in chapter 3.

23. Hucho W H., *Designing Cars For Low Drag - State of The Art and Future Potential*, Impact of Aerodynamics on Vehicle Design (ed. Dorgham M) 1983

24. Howell J P and Bardwell R, *Aerodynamics of 4x4 Vehicles*, Unpublished Presentation, February 1996

25. Janssen L J and Emmelmann H J, *Aerodynamic Improvements - A Great Potential for Better Fuel Economy*, SAE 780265, 1978

26. Morelli A, *The Body Shape of Minimum Drag*, SAE 760186, 1976

27. SAE Standards Committee, *Cross Wind Facilities and Procedures*, SP-1109, May 1995

28. Sumitani K and Yamada Y, *Development of "Aero slit" - Improvement of Aerodynamic Yaw Characteristics for Commercial Vehicles*, SAE 890372, 1989

The crosswind sensitivity of vehicles will be further affected by an anticipated climate change. A report published by the department of the environment²⁹ has highlighted possible changes in future UK weather conditions. The report is based on various results of meteorological climate change models caused by the enhanced greenhouse effect and has, amongst others, the following conclusions:

1. By 2050 the extreme daily average wind speeds in northern UK will increase by 15% for winter conditions and 5% for summer conditions.
2. By 2050 mean winter speeds will increase by 6% in southern England and by 1% in Scotland.

The data implies that within fifty years the country will become subject to increasing high-level winds. For car manufacturers this requires an improvement in aerodynamic design if the future vehicles are to have the equivalent crosswind stability as the present day.

2.5 Conclusions

This chapter has introduced commonly used terms in crosswind aerodynamics and described why crosswind sensitivity is a concern.

In the future the crosswind stability of passenger vehicles will be affected for the following reasons:

1. Environmental legislation will enforce an improvement in fuel efficiency. This will cause:
 - (a) Vehicles to become lighter and so decrease tyre reactions
 - (b) Vehicles to have a lower drag coefficient
2. Climatic change will cause higher gust speeds

All the above cause increased crosswind sensitivity of road vehicles. Sports utility vehicles that previously relied upon their mass to counteract instabilities in crosswinds and that at present are not streamlined will be particularly affected.

29. Parry M L, Review of the Potential Effects of Climate Change in the United Kingdom 2nd Report, Dept. Environment Report, HMSO 0-11-753290-8, June 1996

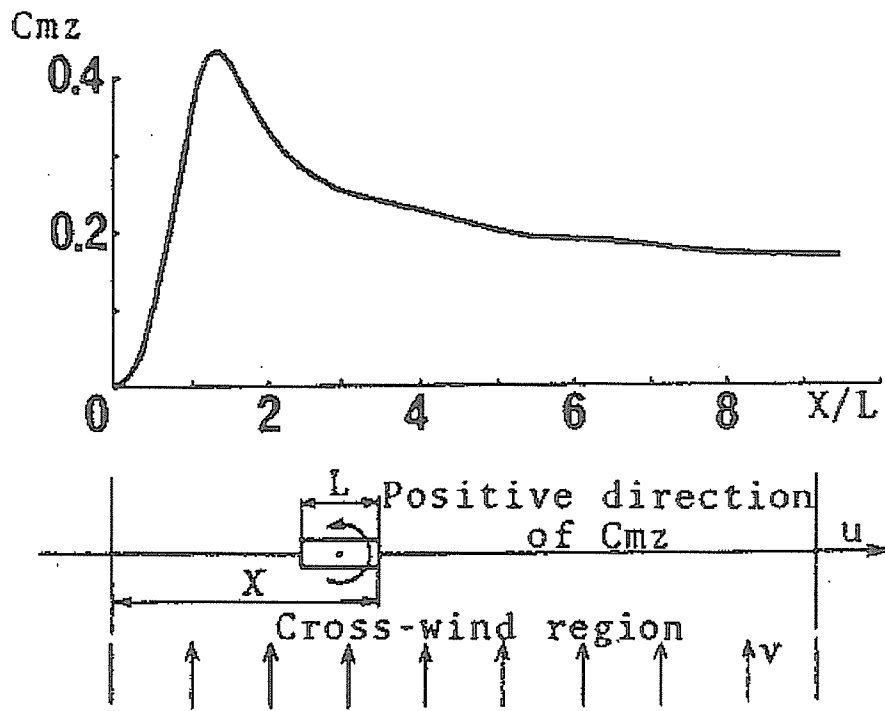


Figure 2-1 Increased Transient Response of Aerodynamic Yawing Moment. After Kobayashi¹⁴

3. Methods to Decrease Crosswind Sensitivity

3.1 Introduction

This chapter discusses how a vehicle can be designed to limit crosswind instabilities and what methods are used to assess crosswind sensitivity. An accurate aerodynamic design can only be achieved using the correct test technique and the recording of aerodynamic response parameters. This is conventionally performed by analysis of force and moment data collected during wind tunnel tests. Test philosophy is discussed and the specific shape changes that influence the aerodynamic force and moment coefficients are identified.

3.2 Experimental Methods of Crosswind Testing

The techniques available to assess the aerodynamic performance of a vehicle in a crosswind can be separated into the following:

- Full Scale Tests
 - Crosswind Generator
 - Wind Tunnel
- Model Scale Wind Tunnel Tests
 - Steady state
 - Dynamic - Moving model
 - Secondary Gust Source

Steady state full-scale wind tunnel tests are closely representative of on-road conditions. All finishing details of the vehicle are included and the test method accurately simulates the Reynolds number. However, the results cannot be used for product development without incurring significant manufacturing costs. In addition the test method does not replicate the correct skewed velocity profile or transient nature of a crosswind gust. The skewed velocity profile is the resultant of the vehicle velocity profile and the velocity profile of the atmospheric boundary layer (Figure 3-1). Macklin³ has shown that a skewed profile gives conservative aerodynamic coefficients compared to the non-skew case.

Full-scale tests with a crosswind generator can represent the transient effects of a crosswind gust and the correct simulation of moving ground but not the skewed velocity profile. They have the advantage that other influences on crosswind vehicle response can be monitored. For example, Howell was able to investigate how the distribution of mass affects vehicle crosswind sensitivity and Macadam⁵ analysed driver evaluations of crosswind sensitivity. Disadvantages are that full-scale tests are not performed in an exactly controlled environment and are conducted at too late a stage in the product development process to be used as a design tool. Data collection on a moving vibrating platform additionally complicates on-road testing.

All of the scale model tests are disadvantaged over full-scale because of inaccurate Reynolds number simulation, though this is dependent on model complexity. Reynolds number simulation of scale models becomes less important with fewer vehicle details and simplification towards bluff bodied shapes. A discussion on Reynolds number sensitivity for the models tested in this research is included in the relevant chapter.

When the scaling of Reynolds number is accounted for, scale model tests have the advantage that they can be used in the design process without significant costs. The most common method is steady state testing where a vehicle model is placed in the wind tunnel (sometimes with a rolling road) and the aerodynamic response measured at various yaw angles to the flow. Simulations of a moving ground primarily influences lift and are important for vehicles with a low ground clearance, such as racing cars, where a fixed ground test would considerably underestimate³⁰. Steady state tests are not a true comparison to actual conditions because they cannot reproduce the skewed incident wind profile and transient responses cannot be monitored.

There are two available methods to simulate the transient nature of a crosswind gust. The first is where a scale model located on a track is propelled across a simulated crosswind gust. This is the only available method to simulate the skewed velocity profile in conjunction with a moving ground surface. Moving model investigations have been previously been performed by Coleman³¹ at the University of Nottingham on 1/50 scale goods vehicles and by Cairns³² and Macklin³ at Cranfield University on 1/6 scale passenger cars. Disadvantages of the moving model method are that the support sting slot interferes with underbody flow and data is corrupted by noise generated by the moving model. In the second transient test method³³, a stationary model is mounted in an open jet wind tunnel and the transient crosswind component is provided by a second open jet set adjacent to but at an angle with the main jet. Sequentially opening shutters on the second jet create the gust effect. This method has the benefit of low data noise, but the approach can only provide data at a fixed peak yaw angle and which must also be relatively high (30°).

The different techniques to reproduce transient crosswinds all differ slightly in their simulation. The gust in the moving model approach is the most controllable but produces a gust that is sharper (i.e. too sudden) than provided by real life conditions. Ramping of the gust in full-scale tests using crosswind generators can accurately simulate real life conditions but as mentioned previously, can only be used as a final assessment rather than a design tool. The secondary gust source technique used for testing scale models also suffers from uncertainty of flow mixing between the two jets at the gust interface.

30. Cooper K R, Bluff Body Aerodynamics as Applied to Vehicles, JWEIA Vol. 49, pp. 1-22, 1993

31. Coleman S A, The Aerodynamics of Ground Vehicles in Crosswinds, Ph.D. Thesis, University of Nottingham, 1990

32. Cairns R S, Lateral Aerodynamic Characteristics of Motor Vehicles in Transient Crosswinds, Ph.D. Thesis, Cranfield University, 1994

33. Dominy R G and Ryan A, An Improved Wind Tunnel Configuration for the Investigation of Aerodynamic Crosswind Gust Response, SAE 1999-01-0808, 1999

3.2.1 Analytical Models

Because of the inaccuracies inherent in scale wind tunnel testing and the lack of design benefits for full-scale tests, several authors have developed analytical models to describe the response of a vehicle in a crosswind. Many of these are based on aerodynamic tests such as Macadam⁵ who used the results of full-scale crosswind generator tests to develop a dynamic crosswind model and Klein⁷ who used a similar method. An analytical model was then developed based on simplified vehicle equations of motion describing the yaw velocity and side velocity response to steering angle and side gusts. However, the model could only be used to predict yaw response to a crosswind disturbance to within 50% of the measured value. Wallentowitz³⁴ considered that crosswind generators do not replicate real road conditions and specifically the frequencies that occur in transient conditions. To address this problem, an on-road device was designed to measure the wind velocity above a moving vehicle and so represent the natural frequencies of interest. Wind velocity is measured by a Pitot tube and wind vane placed on the vehicle above the roof so as not to be influenced by the vehicle shape. An analytical model is then developed based on this data that can assess the influence of driver interaction in real road conditions. The fact that analytical models based on full-scale crosswind generator tests can include driver influence in their simulation can be seen as an advantage or disadvantage depending on your viewpoint. As mentioned previously in section 2.2 the driver is an important component in vehicle response but it is an additional variable to monitor and the average driver is very hard to define.

Baker³⁵ has conducted much work in the field of analytical models and found that for simple 1-box shapes, force and moment histories in the time domain were in good agreement with experimental data. The analytical method used was based on the convolution integral relating aerodynamic force time histories, wind velocity histories and an aerodynamic weighting function to obtain the aerodynamic admittance of a vehicle. The method assumes that the vehicle length is small when compared to the wind gust but this is not always the case. In such conditions an aerodynamic weighting function must be used to modify the equations. Another analytical model developed by Baker³⁶ is based on vehicle displacement spectra to assess vehicle stability. The analysis method takes the spectrum of the natural wind and multiplies it by an aerodynamic admittance and a vehicle transfer function to give the vehicle displacement spectra. The vehicle transfer function is obtained from a solution of the basic equations of motion for the vehicle considering aerodynamic forces and moments as well as tyre reactions, vehicle mass and allowances for driver behavior. The model was in agreement with experimental data if the

34. Wallentowitz H and Schaible S, Crosswind Behaviour of Passenger Cars under Natural Conditions, AVEC 1998 (1998.9), Paper No 9837463

35. Baker C J, Ground Vehicles in High Crosswinds Part 2: Unsteady Aerodynamic Forces, J. Fluids and Structures, vol. 5, pp91-111, 1991

36. Baker C J and Robinson C G, The Assessment of Wind Tunnel Techniques for Ground Vehicles in Crosswinds, JWEIA vol. 33, pp429-438, 1990

aerodynamic coefficients are known over a wide range of yaw angles. However, the assumptions made in forming the vehicle transfer function are too imprecise at present to be used as a design tool and will require continued analytical development.

Analytical models are flawed in that they are based on previous aerodynamic measurements but are still useful in analysing other components of the total vehicle crosswind response. For example, Takada⁸ was able to show that suspension characteristics and roll steer compliance on a 1-box type vehicle have a greater influence on crosswind stability than different aerodynamics. However, the influence is still subject to change since the calculation of handling characteristics is based on initial aerodynamic inputs. Other examples include Bucheim⁴, who was able to include all the inputs of the vehicle response and combine them into an index of vehicle stability. The influence of each parameter could then be compared and assessed within the total response.

Analytical models form a sound basis to classify the crosswind response but are dependent on initial aerodynamic inputs. Therefore the flow mechanisms that generate aerodynamic forces first need to be fully understood.

3.3 Wind Tunnel Test Philosophy and Modeling Technique

To correctly predict accident risk for a particular vehicle shape, Baker³⁷ states that the variation of aerodynamic forces and moments and surface pressure distributions around the vehicle are required. The mean values of the aerodynamic forces and moments will depend upon:

- Vehicle geometry
- Vehicle velocity
- Fluid properties
- Wind characteristics - turbulence intensity and scale, boundary layer height and angle of yaw

Further to this, Baker³⁷ conducted dimensional analysis of the problem and concludes that to be an effective model the following dimensionless groups must be correctly simulated:

- Reynolds number
- Model Geometry (length ratio)
- Yaw angle
- Velocity variation with height
- Turbulence intensity variation with height
- Turbulence scale variation with height

37. Baker C J, Ground Vehicles in High Crosswinds Part 1: Steady Aerodynamic Forces, J. Fluids and Structures, vol. 5, pp69-90, 1991

- Turbulence intensity at reference height
- Turbulence scale at reference height
- Skewed boundary layer profile

For certain vehicle shape configurations Macklin³ showed that the aerodynamic coefficients are Reynolds number dependent below $Re = 4 \times 10^5$. Cooper³⁸ suggests that one third of full scale Reynolds number is acceptable (1×10^6) based on model width or the square root of frontal area. The correct simulation of Reynolds number is more important for streamlined models where a higher Reynolds number is necessary for reasonable simulation. ESDU force data of rectangular blocks³⁹ found that no significant trend or variation with Reynolds number is apparent between 10^4 and 10^6 .

For scale model testing the correct simulation of turbulence scale is very difficult to achieve in the wind tunnel. Macklin⁴⁰ investigated a number of turbulence intensity regimes on passenger vehicles but concluded that there was little effect of turbulence on the vehicles aerodynamic coefficients. In other work on the effects of turbulence intensity on side forces⁴¹, it was found that for a given yaw angle and turbulence intensity, the force spectra are invariant of car configuration, therefore independent on detailing and radius. It was also found that for all vehicle shapes the unsteady side force increases with increasing turbulent winds but that the mean force is only slightly altered.

3.4 Assessing an Aerodynamic Design

There are 3 methods to quantify the effects of a crosswind on a moving vehicle:

- Examination of the aerodynamic coefficients
- Pressure Mapping
- Flow Visualisation

The collection of aerodynamic force and moment data is the most popular technique to assess the aerodynamic response of a vehicle in a crosswind. This is because the collection of data is relatively simple and there is a large database to compare and contrast for each vehicle shape. However, measurement of aerodynamic forces does not reveal the contributions from specific regions to the overall pressure difference and this can only be achieved by recording the surface pressures on the model itself.

38. Cooper K R, The Wind Tunnel Simulation Of Surface Vehicles, JWEIA vol. 17, 1984

39. ESDU Data Sheet, Fluid Forces, Pressures and Moments on Rectangular Blocks, 71016, September 1971

40. Macklin R, Garry K and Howell J, Assessing the Effects of Shear and Turbulence During the Dynamic Testing of the Crosswind Sensitivity of Road Vehicles, SAE 970135, 1997

41. Nguyen T M, Saunders J W and Watkins S, The Sideways Dynamic Force on Passenger Cars in Turbulent Winds, SAE 970405, 1997

Pressure contour maps are essential in determining fluid flow effects about bluff bodies but due to their complexity they are rarely performed. Howell⁴² conducted a full-scale steady state wind tunnel test on a Rover 800 saloon car and took 870 pressure tappings at 3 different angles of yaw to assess the contributions to the overall pressure from certain regions. The horizontal pressure distributions from 3 different yaw angles at a section through a Rover 800 saloon are shown in Figure 3-2. The figure clearly shows the large negative pressure at the A-pillar that is partly responsible for a high yawing moment at higher angles of yaw. The data shows that for this particular shape the A-pillar region is the greatest contributor to the overall side force and that the front of the vehicle contributes the most to the aerodynamic yawing moment.

Flow visualisation techniques can determine flow structure and are a useful tool when used in conjunction with force and moment data. There are several methods:

- Application of tufts or paint
- Introduction of smoke into the flow

The first method is limited because it only visualises flow close to the model surface and the presence of tufts can alter the flow. Smoke visualisation produces a more comprehensive picture of fluid flow but suffers from its own drawbacks. Foremost is that the smoke particles have to be small enough to follow the flow but large enough to enable photographic capture.

3.5 Vehicle Aerodynamics

This section details the individual shape changes that will yield a different aerodynamic response when a moving vehicle is subjected to a crosswind. There are two objectives from an aerodynamic design, often seen as the most important is reduction of the drag coefficient in order to improve fuel efficiency. The second is driving stability which can be separated into straight line driving where lift and pitch are important and crosswind sensitivity which is primarily influenced by the aerodynamic yawing moment and side force distribution.

3.5.1 Straight Line Driving Aerodynamics

The response of a vehicle when subjected to airflow is strongly characterised by flow separation. Gilhaus⁴³ showed that the rounding of edges at the front of the vehicle to prevent flow separation is the main component in order to produce low drag and aerodynamic efficiency. Flow separation at the rear of the vehicle is much more complex. Morel⁴⁴ conducted research on the slant angle of hatch back cars after previous research had showed there to be an abrupt increase in the drag coefficient at slant angles of between 25 and 35° (Figure 3-3). This

42. Howell J P, The Side Load Distribution on a Rover 800 Saloon Car Under Crosswind Conditions, JWEIA vol. 60, 1996

43. Gilhaus A M and Renn V E, Drag and Driving-Stability-Related Aerodynamic Forces and Their Interdependence - Results of Measurements on 3/8 Scale Basic Car Shapes, SAE 860211, 1986

44. Morel T, Aerodynamic Drag of Bluff Body Shapes Characteristic of Hatchback Cars, SAE 780267, 1978

was attributed to a change in the near wake flow pattern at a critical slant angle. Fluid flow could be separated into two regimes: above 42° the flow was quasi-axisymmetric and below this angle, the separation pattern was characterised by strong vortices originating from the C-pillar (Figure 3-4). The high negative pressures developed by these vortices were thought to be responsible for the increased drag coefficient below 42° . Research was then focused on other factors that would influence the formation of the trailing vortices such as the effects of ground proximity, freestream turbulence and the rounding of edges. Of these the rounding of the cantrail had the more pronounced effect and caused a shift in the maximum drag coefficient to a higher slant angle. This provides drag benefits for the below critical angle case but is detrimental above the critical angle. Moreover, the influence of slant angle was found to be increasingly important when the model was yawed to the incident wind and where the overall drag coefficient is greater.

Other results⁴³ confirmed those of Morel on backlight angles and radiusing and also showed that increasing boot height and length decreased drag as well as lift. Drag could also be significantly improved by tapering (plan view) of the rear of the vehicle. Howell⁶ also provides confirmation of the influence of backlight angle. The results of scale model wind tunnel tests show a decrease in drag coefficient with change of backlight angle up to 15° backlight angle that then rises with a sharp peak at 30° . By applying planform curvature, an improvement was made in the drag coefficient for all vehicle configurations apart from the squareback case (2-box or estate).

Investigations by Bucheim⁴ into the influence of lift in the absence of crosswinds concluded that cars with negative aerodynamic pitching moment show decreased directional stability compared to those with a positive pitching moment. A vehicle is defined as stable if it continues on its directed path without additional steering input. It was also noted that lift influences directional stability mainly at high speeds and overall a positive pitching moment at a lower overall lift is desirable for good directional stability. In investigating the influence of the aerodynamic shape on lift, it was found that methods to optimise for reduced lift at the front axle often conflicted with reducing the drag coefficient. It was also shown that square or hatch back cars gave optimum rear axle lift values and that optimisation of drag was coincident with optimisation of rear axle lift for fastback cars.

3.5.2 Crosswind Aerodynamics

Kohri⁴⁵ classified the change of the yawing moment and side force coefficients with yaw into two distinct regions. In region 1 below 22° yaw angle the flow is characterised by vortices at the leeward front corner, A-pillar and windward C-pillar. Separation and reattachment of the flow occurs and negative pressure is generated between these points. In the second region above approximately 22° separation of the flow starts to occur and the corner vortex at the A-pillar disappears. The negative pressure created by the vortex is thus released and

45. Kohri I and Kataoka T, Research on Improvement of Crosswind Properties of Passenger vehicles, JSAE review, vol. 10, No. 3, 1989

an improvement in the yawing moment coefficient is made. Barth⁴⁶ demonstrated the influence of flow separation on the aerodynamic yawing moment as early as 1960. Figure 3-5 shows pressure measurements of a then typical saloon vehicle subjected to a crosswind at 15° yaw. The concentration of the large negative pressure at the front of the vehicle on the leeward side is largely responsible for a high yawing moment. Furthermore it is inherently unstable since the action of turning the nose of the vehicle leeward increases the negative pressure. The negative pressure increases up to a critical yaw angle when flow separates at the leeward front fender corner and the negative pressure in this region is decreased.

Other work⁶ found that the effects of edge radiusing on improving the yawing moment is hard to quantify with some edge rounding being beneficial and some not so. This largely depends on whether the modification prevents flow separation in the yawed state. For example, if flow is allowed to separate vortical flow is prevented and the negative pressure in that region decreases resulting in a lower yawing moment coefficient. Edge radiusing of the fender prevents flow separation and increases the aerodynamic yawing moment.

In evaluating the yawing moment and side force contributions to vehicle stability in the presence of a crosswind, Bucheim⁴ concluded:

- Side force is not as important as yawing moment in influencing crosswind sensitivity
- To decrease front side axle force, flow separation at the leeward edges of the fender and A-pillar must be induced. Flow separation can be achieved for small yaw angles by minimising the edge radius and plan view tapering of the front vertical edges
- A square back (2-box type) is more favourable than a fast or notchback

Although aerodynamic crosswind response is primarily influenced by side force and yawing moment, lift also contributes to overall stability. Rauser⁴⁷ notes that for optimal crosswind stability, neutral or slightly positive lift at the front axle is best combined with rear negative lift or rear neutral lift. Kohri⁴⁵ investigated the influence shape changes at the rear of fastback and notchback vehicles had upon yawing moment. It was concluded that the strength of the windward C-pillar corner vortex is the primary factor influencing the aerodynamic yawing moment at the rear of the vehicle, the strength of which is dependent on:

- Decreased backlight angle
- Increasing height of backlight slant
- Increasing C-pillar edge radii.

46. Barth R, Effect of Unsymmetrical Wind Incidence on Aerodynamic Forces Acting on Vehicle Models and Similar Bodies, MIRA Trans. 15/60, ATZ March 1960

47. SAE, Closed-Test-Section Wind Tunnel Blockage Corrections for Road Vehicles, SAE SP - 1176, 1996

When the slant angle is a small value as is the case for 1 and 2-box type vehicles, the C-pillar vortex becomes weak and the rear side area then largely influences the aerodynamic yawing moment.

Gilhaus⁴³ showed that an increase in boot height and length increased the yawing moment, as did a lower overall side area resulting from a change in backlight angle, but the most notable rises in yawing moment arose from rear edge radiusing. Plan view tapering of the C-pillar was found to have a detrimental effect on yawing moment and was attributed to the fact that the rear side area is effectively reduced.

A series of wind tunnel tests to investigate shape changes that influence crosswind sensitivity⁶ found that yawing moment rises steadily with change of backlight angle up to 25° and also by rounding the edges of the vehicle. Planform curvature improved the yawing moment coefficient as did open wheel design. It was concluded that for improved crosswind sensitivity, all vehicle shapes would benefit from:

- Reduced front overhang
- Lower front spoiler
- Reduced air intake
- Increased wing crown curvature
- Reduced side area forward of mid-wheelbase
- A-pillar curvature
- Rounded front header
- Increased planform curvature

The influence of front spoiler is confirmed by Okumura⁴⁸ who found that during tests on a 1-box type vehicle, a front spoiler could reduce the yawing moment by approximately 20%. This was because the change in flow structure caused a reduction in peak pressures at the leeward fender.

From the limited work published on SUV's⁴⁹, the A-pillar and front end of the vehicle primarily influence the side force coefficient with the front end having most pronounced affect on the yawing moment. It was also found that it is the higher surfaces (cantrail) at the rear of the vehicle that contributes to the aerodynamic side force.

3.5.3 Discussion on Crosswind Aerodynamics

One of the problems the aerodynamicist has to undertake is that the optimisation of the aerodynamic coefficients often produces conflicting goals.

48. Okumura K and Kuriyama T, Transient Aerodynamic Simulation in Crosswind and Passing an Automobile, SAE 970404, 1997

49. Docton M K R and Dominy R G, The Side Load Distribution on a Range Rover Under Simulated Crosswind Conditions, paper presented at WES Conference, 1996

The aerodynamic parameters that influence straight-line driving and crosswind sensitivity when considered separately have been established but it is when the two are combined that the understanding becomes complex. Designing a vehicle for ideal ride for straight line driving is different to that for crosswind stability or in other words, the actions to improve drag and lift do not necessarily improve the side force distribution and yawing moment. Gilhaus⁴³ noticed that reduction of the drag coefficient often had a detrimental effect on the other aerodynamic coefficients and particularly those related to driving stability. Additionally, the prevention of flow separation by radiusing is necessary to produce low drag but the effects of radiusing has an adverse affect on lift as do the majority of shape modifications used to produce low drag.

Other attempts to attain a low drag shape whilst maintaining crosswind stability found that shape modifications at the front of the vehicle can be beneficial for all coefficients but there is conflict with modifications at the rear of the vehicle⁴⁵. It was additionally noted that C-pillar edge radii and tapering at the rear have a pronounced effect of the ratio of drag and yaw coefficients.

An important aspect of designing to improve crosswind sensitivity is that public perceptions and not aerodynamics dictate vehicle shape. A review³⁸ of the present state of aerodynamics in 1984 quoted the phrase of 'perceived aerodynamics' that was at the time being used by car designers. This implies that the designers are happy with the appearance of aerodynamics but not the functional capability. This is evident in modern cars that have become rounder at the front and rear. Rounding of the front of a vehicle has helped greatly in the reduction of the drag coefficient. However, no great advantage in the aerodynamic coefficients is realised from rounding of the rear but from a stylists view it is deemed essential to form a pleasing appearance. It has been shown by Gilhaus⁴³ that the styling trend of well-rounded rear surfaces actually increases the aerodynamic yawing moment.

Aerodynamic research that has been conducted on one and 2-box type vehicles has been limited to reduction of the drag coefficient and often neglects crosswinds. From the limited research available, it is evident that the aerodynamic response of an SUV is vastly different to that of conventional passenger cars. This is largely due to the specific shape differences that distinguish the vehicle's class. They are:

- Increased rear side area
- Large ground clearance
- Bluff front end to give off-road appearance

and all contribute to increased aerodynamic forces and moments.

3.5.4 Flow Control Methods of Reducing Aerodynamic Yawing Moment

It has been shown in the preceding sections that it is the negative pressure at the front leeward fender that is largely responsible for a high aerodynamic yawing moment. If this negative pressure is released by inducing separation of

the flow the yawing moment can be significantly reduced. The penalty of this separation of the flow is an increase in drag but two methods have been devised to optimise yaw moment as well as drag:

- Hucho⁵⁰ on his work of light vans found that the area of negative pressure at the leeward corner could be suppressed by optimising the vehicle for separation free flow between $\pm 10^\circ$ yaw. In this region side winds are of relatively little concern but at larger yaw angles where there is potentially a problem the flow is tripped to separate at the front fender. This of course increases drag but it can be tolerated since yaw angles of this magnitude are of a rare occurrence.
- To induce separation, the front fender pressure is increased by introducing air ducted from a point at the front of the vehicle chosen to give the maximum possible pressure gradient. This ducted flow method²⁸ - termed 'aeroslit' - was later applied to full-scale vehicles and gave a 15% improvement to lateral deviation and maximum yaw rate. Driver perceived effects are that aeroslit reduces the shock when entering a cross wind, reduces the required frequency of steering wheel correction and enhances cross wind stability.

3.6 Conclusions

The conclusions from this chapter are:

1. A moving model test is a realistic and cost effective method to adequately model transient conditions.
2. The conventional methods of describing vehicle response in terms of the aerodynamic forces and moments are insufficient for a detailed aerodynamic design. Pressure mapping is a better method to determine overall fluid behaviour and can reveal the influence of specific areas on the vehicle to the overall response.
3. Shape changes implemented to improve drag coefficients are directed at reducing flow separation. These shape changes often conflict with the reduction of side force and yawing moment coefficients.

50. Hucho W, *Aerodynamics of Road Vehicles* (ed. Hucho W.), 1987 Butterworths

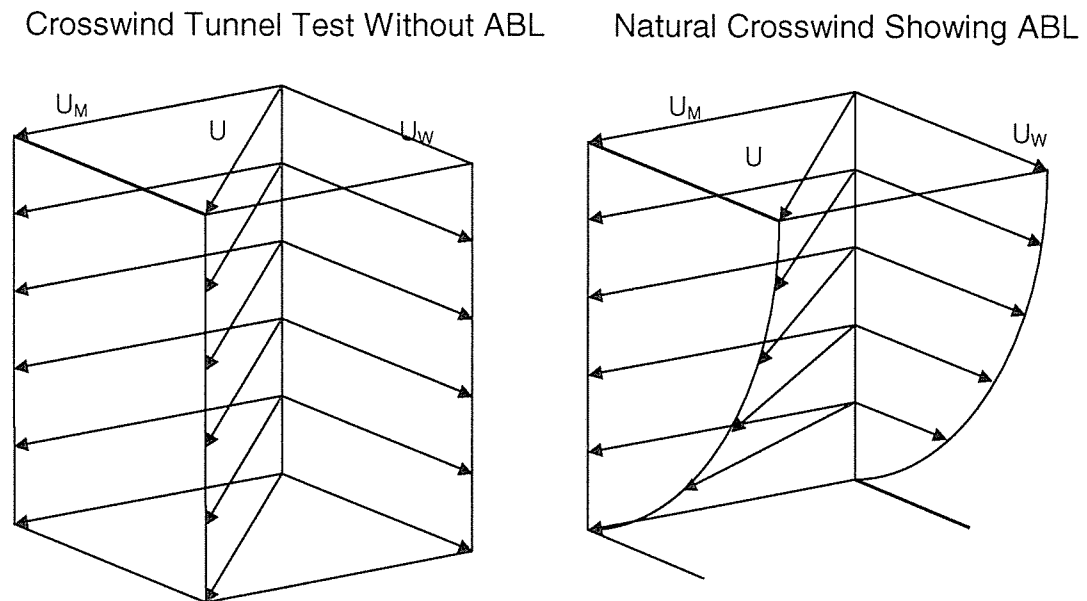


Figure 3-1 Different Velocity Profiles to Show Skew

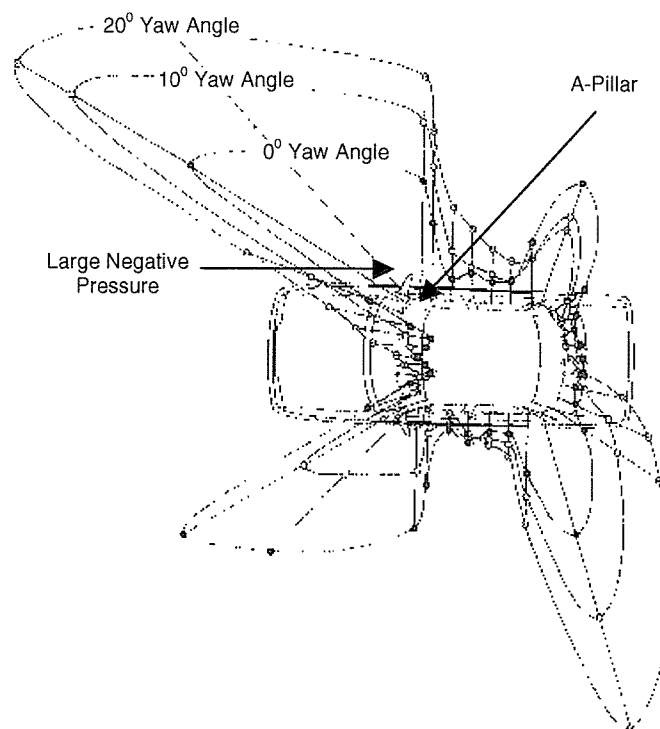


Figure 3-2 Pressure Map of Rover 800 Saloon. After Howell⁴²

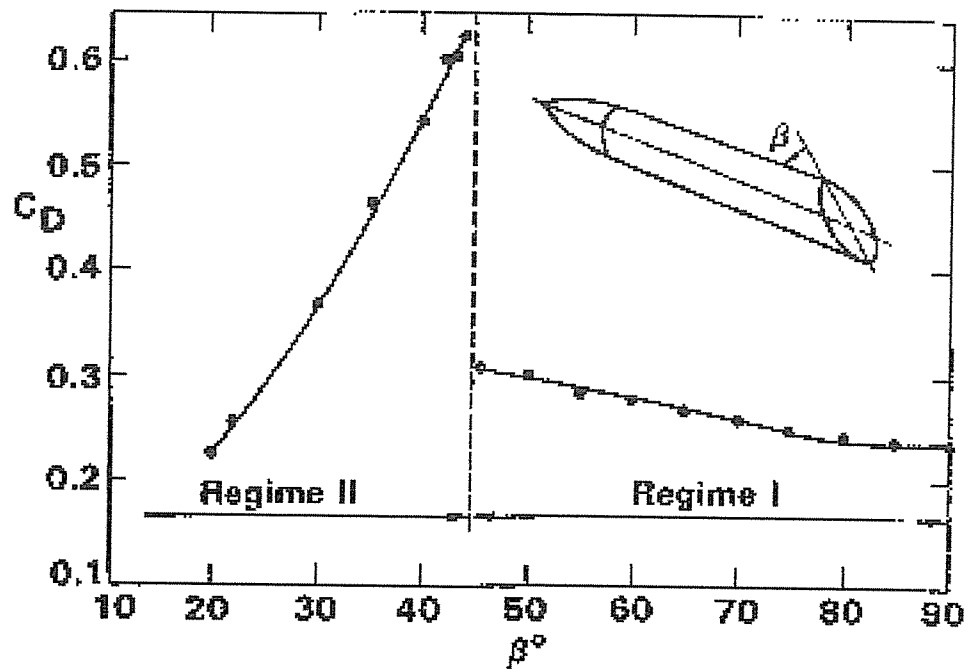


Figure 3-3 Variation of Drag Coefficient with Backlight Angle. After Morel⁴⁴

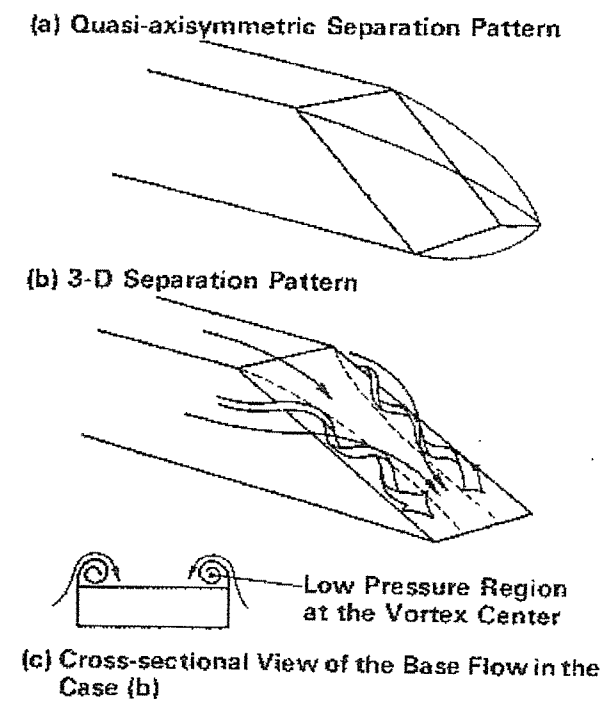


Figure 3-4 Formation of Vortices at the Rear of a Vehicle. After Morel⁴⁴

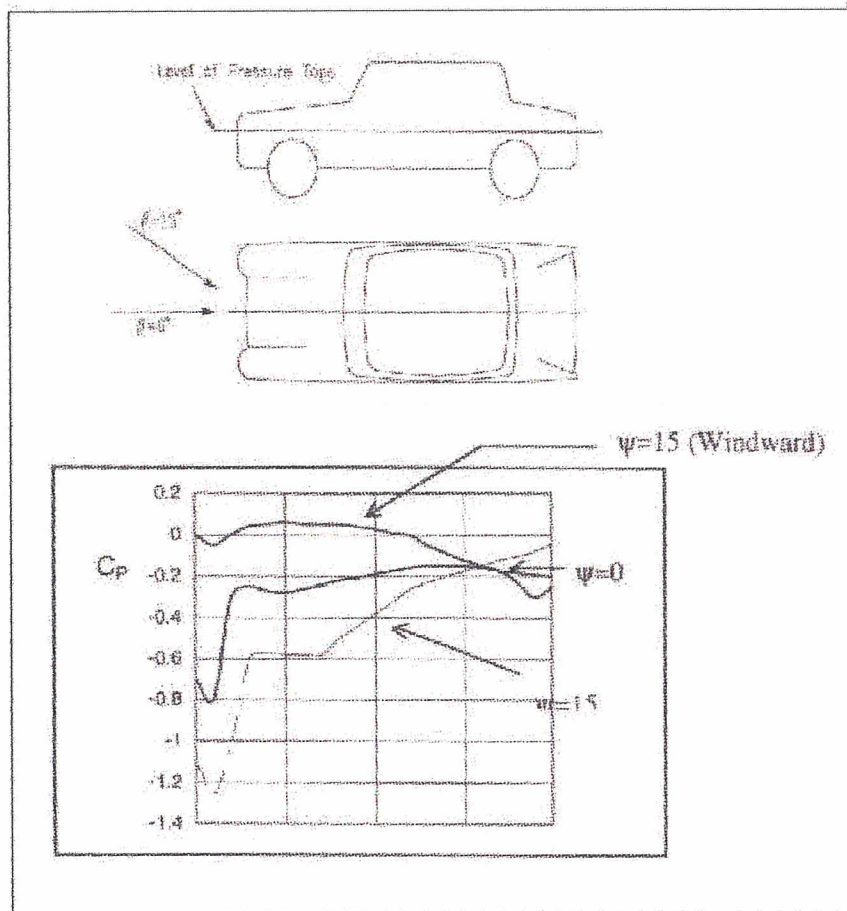


Figure 3-5 Generation of Leeward Negative Pressure on a Typical Saloon. After Barth⁴⁶

4. Experimental Equipment

4.1 Introduction

This chapter details the experimental facility and test methods used in this research. Collection and data reduction of data is discussed and the dynamic pressure measurement system developed in this research is also described. Modifications to the test facility to improve data quality are shown. A comparison of typical obtainable data and previously collected data from Macklin³ before implemented track improvements is contained in appendix A.

4.1.1 Development of The Cranfield Crosswind Facility

In 1990 the College of Aeronautics at Cranfield University in conjunction with Rover Group started a long-term program of work to investigate the transient crosswind response of road vehicles. The core of the program was to simulate transient flow conditions and a purpose built facility was developed initially by Cairns³² and later by Macklin³. The test facility was used to understand the flow characteristics of passenger vehicles under transient conditions by taking aerodynamic force and moment data and by flow visualisation techniques. Further work by Garry et al⁵¹ investigated the transient response of flat plates to gain an understanding of the fundamental nature of fluid flows in transient crosswind conditions. Although successful in their application, the collection of force and moment data in previous investigations has not revealed detailed flow characteristics of transient conditions and the results were often difficult to interpret because of signal noise contamination. An alternative method of understanding transient response characteristics is by pressure mapping of the model surface, the development of which forms a major component of the present research.

4.1.2 Description of The Facility

The crosswind track facility (Figure 4-1) runs perpendicular to the 2.4m x 1.2m boundary layer wind tunnel at Cranfield University. The 17.5m long track is constructed of 150mm x 10mm steel plate supported by steel stanchions and encased in concrete blocks. On the track is a driving and model carriage connected to each other by a solenoid-activated release. The model carriage carries the model itself plus signal amplifiers, hardware filters and a data acquisition board and the driving carriage is connected to a winch at the firing end of the track enabling the model carriage to be pulled back under bungee tension to the appropriate firing position. Activation of the solenoid releases the model carriage that is then accelerated by the bungees along the track. Before entrance to the tunnel, an arrestor hook captures the accelerator bungee and the model carriage coasts across the working section of the wind tunnel. A set of LED sensor's positioned at the side of the track triggers data collection and

51. Garry K P, Macklin A R and Opstal E P E, Measurement of Transient Aerodynamic Loads on Bluff Bodies at Extreme Yaw Angles, RAeS Conference on Vehicle Aerodynamics, Loughborough UK, 1994

calculates the speed of the model carriage. At maximum tension the bungee can accelerate the model up to 25m/s with a typical deceleration across the working section of 0.2m/s (0.8%). Once past the crosswind gust, an arrestor bungee at the far side of the track decelerates the model carriage and sends it back through the wind tunnel. The acquisition board can then be connected to a PC to download force or pressure data.

4.1.3 Wind Tunnel Set-up

The 2.4m by 1.2m working section boundary layer wind tunnel is operated at a windspeed of 13m/s for steady state tests. For transient tests, the tunnel wind velocity is chosen to represent the required yaw angle given a constant model velocity of approximately 13m/s. A higher test wind speed is desirable for Reynolds number simulation but was chosen to enable the fluid flow around the model to approach a quasi-steady state during the time in the crosswind gust.

A groundboard (Figure 4-2) either side of the track removes the wind tunnel floor boundary layer and ensures the freestream velocity was uniform over the height of the model. Slots in the groundboard to allow passage of the model were adjusted to give the minimum gap for dynamic tests without touching the support sting. The groundboard is continuous to 1m or 2 model lengths either side of the working section of the wind tunnel to ensure freestream flow conditions are established before entrance to the gust. For steady state tests, an identical groundboard but without slots was used with a flush fitted turntable to orientate the model to the desired yaw angle.

Wind tunnel dynamic pressure was measured using a Pitot static probe in a permanent position upstream of the crosswind track (Figure 4-2). Figure 4-3 shows the variation of the working section static pressure between the plane of the track and the freestream pressure measurement point. A test to determine this static variation was conducted at constant tunnel velocity with the groundboard slots fully closed and at mid model height. The figure shows the difference in up and downstream static pressure non-dimensionalised by the freestream dynamic pressure. The gap in the wind tunnel walls to allow passage of the model is from distance -340 to -940mm from the freestream measurement point and the plane of the track is at -600mm. It can be seen that the variation of freestream static pressure is approximately linear across the model path and approaches a steady value at approximately -650mm.

Since the variation of static pressure is directly proportional to the dynamic pressure, as shown in Figure 4-4, the error could be subtracted once the final pressure coefficients were calculated. The value of the pressure coefficient offset was dependent on how much the groundboard slots are open or closed and was also accounted for in subsequent data reduction.

Variations in freestream dynamic pressure and freestream static pressure on entrance to the wind tunnel section in the plane of the track are shown in Figure 4-7 and Figure 4-8 respectively. The dynamic pressure variation presented in Figure 4-7 is in agreement with a detailed gust survey by Macklin³ and confirms

that freestream conditions are established within 35mm of entering the crosswind gust.

4.2 Track Improvements

On commencement of the project, track improvements first had to be carried out to address the following problems:

- Zero drift of the balance output signals
- Repeatability of track signatures
- Excessive noise in the balance output signals

that will now be considered in turn.

4.2.1 Zero Drift of Balance

Previous data reduction methodology had been to take a zero balance reading before and after wind-on data was recorded. The average of the two zero readings was then subtracted from the raw data wind-on signal. Macklin³ considered this necessary because it was unsure if the drift of the balance was caused by the accelerating or decelerating loads when the carriage was fired. An examination of the balance signal showed that the large inertial loads imparted to the carriage from the original friction brake system created the largest balance response and it was thought that this was the main cause of balance signal drift. This meant that the recording and subtraction of the after run zero balance reading was incorrect and would corrupt the results. In addition to this, the vigorous nature in which the friction brake slowed down the model carriage could cause possible damage to the model and balance. It was concluded that a redesign of the brake system would considerably reduce the zero drift of the balance and reduce the possibility of damage to the balance and model.

4.2.1.1 Replacement of the Braking Mechanism

A replacement design for the brake mechanism that also incorporated automatic return of the model had already been devised but had not been implemented. In this design (Figure 4-5), the model carriage was initially decelerated by an arrestor bungee at the far end of the track and on its return captured by a second carriage (also restrained by a bungee) on a separate track beneath the model. After equilibrium between the two bungees was achieved a solenoid on the capture carriage was activated which released the model carriage and sent it back across the wind tunnel working section ready for another run. The bungee lengths were chosen such that on release there was just enough force to propel the model carriage back across the working section.

On application this design was unsuccessful for the following reasons:

- The capture carriage had too high a mass
- Inappropriate bungee caused rapid deceleration

- The solenoid was not powerful enough to release the model carriage under the bungee forces.
- The restraining point of the arrestor bungee prevented free travel of the capture carriage

As a result a higher shock load was generated on the model carriage than that caused by the original friction brake system. This both damaged the model and caused a high balance zero drift with resulting loss of confidence in the track signatures. Improvements to the above system proved unsuccessful and a new design was proposed based on equilibrium of bungee forces but without automatic return. In this system (Figure 4-6), the model carriage was decelerated initially by an arrestor bungee and on its return captured by a second bungee. The model carriage was thus restrained in either direction and energy was dissipated gradually till the carriage came to a halt. This simple design proved very successful and the zero drift of the balance was significantly improved.

After implication of the new braking mechanism a single zero reading is now taken before the run data.

4.2.2 Repeatability of Track Signatures

Previous data is acknowledged as having poor repeatability and an examination of the track revealed the following inconsistencies in data collection:

- The track was dirty and small indentations were found on the surface
- Joins between the 6m length steel plates comprising the track were no longer flush to each other and disrupted the smooth running surface
- Some of the bearings for the model carriage were badly worn and no longer in contact with the track
- Damage to the brackets holding the amplifier and data acquisition boards
- The concrete arrestor block for the arrestor bungee imparted a load to the track on firing
- LED holders which translated data to the position domain were not precise enough for the resolution required

The above are all sources of signal noise contamination but it was thought that a lack of standard test procedure was the main cause of inconsistency. Bearing clearance on the model was also found to significantly affect track signature repeatability. Signal repeatability is presented in Figure 4-9, which show the unfiltered aerodynamic coefficients for the sharp edged box model over 12 runs at 0° yaw. Though large signal oscillations are present, they are consistent in magnitude and phase and adequate for the data reduction processed to be described in section 4.5.

4.2.3 Excessive Noise

The possible sources of signal noise were thought to be similar to that responsible for poor repeatability and it was found that after measures to improve track repeatability had been implemented, signal noise was significantly reduced.

4.3 Experimental Models

There are 6 models tested in this research all at approximately 1:8 scale to the aspect ratio of a full scale SUV. The first model tested is the squareback passenger car model used by Macklin³ and is included to show improved data quality after implemented track improvements (Appendix A). The remaining 5 models have been made specifically for this research program and are tested in order of geometric complexity in order to ascertain fundamental features of transient flows. All models with the exception of the Range Rover are tested with a 30mm ground clearance representing 15% of the height of the model.

4.3.1 Flat Plate

The first model to be tested is a simple aluminium flat plate of dimensions 480mm long, 200mm high and 6mm thick. The flat plate model was chosen because it is of similar aspect ratio to a typical SUV and comparisons with previous data collected by Garry⁵¹ using the same model can also be made. The aluminium plate is pressure tapped over an approximate 50mm grid as shown in Figure 4-10. Pressure tappings are also placed as close as possible to the edge of the model (3mm) giving a total of 55 pressure tappings per side. The pressure tappings are formed initially by machining 11 grooves into the plate at the lengthwise tapping locations. A 210mm length 3mm bore tube is then placed into the groove and the groove filled with resin to ensure a smooth surface. The individual pressure tappings of 2mm diameter are then drilled into the common tube at the heightwise tapping locations. By this method, 10 pressure tappings are connected to a common tube, which are then sealed by covering with aluminium tape. Measurement of the pressure at a particular tapping during tests is performed by uncovering only that tapping to be measured with care being taken not to leave adhesive on the opening of the hole and possible corrupting the results.

4.3.2 1-Box model

The 1-box model is of the same dimensions as the flat plate model and 200mm width (Figure 4-11). Unlike the aluminium flat plate, it is constructed of lightweight foam board so as not to increase track noise. The model is pressure tapped on the same grid as that used for the flat plate for each of the two side faces as well as the upper and lower face. The end face is pressure tapped on a 50mm grid with the outermost tappings placed as close to the edge as possible (3mm). Tappings for the 1-box model are in the conventional manner and connected to the pressure transducers via 300mm length 1mm bore PVC tubing. Two configurations of the 1-box model are tested: a sharp edged case

and rounded case with all edge radii of 20mm ($r/h = 0.1$). For the radiused edged case, the outer edgeappings for each face are located at the apex of the radius for all edges.

4.3.3 2-Box Model

Dimensions and pressure tapping locations of the 2-box model are shown in Figure 4-12. Pressure measurement locations were identified from the tests of the 1-box models and are concentrated around the leeward front fender and a-pillar. The 2-box model has a 120mm length 'bonnet' at a height of 100mm and a 51° windscreen angle giving a roof length of 377mm. This is consistent with the aspect ratios of the Range Rover model to be tested as the final model in this research. After problems arose with model deformation with the box models, it was decided to construct the model of a much stiffer material. Carbon fibre was deemed to be the best option because of its improved stiffness together with low mass so not to increase track-induced oscillations. In practice, the carbon fibre model was sufficiently stiff but was too heavy and a second model was made out of solid foam. The model interior was then bored out to hold balance-mounting brackets and to reduce the overall mass.

4.3.4 Range Rover model

The final model to be tested is a 1/8 scale model of the 1996 production Range Rover (Figure 4-13). Initially, the model was constructed using stereo lithography techniques that ensured a fine detailed and accurate replication. Unfortunately, the mass of the model was much heavier than previous models and could cause possible damage to the force balance if tested dynamically. A second model was then constructed in foam that lost body details and surface finish but lowered the mass. Pressure tappings are specifically chosen to investigate the transient flows at the critical locations identified in the 2-box model tests. These are around the leeward front fender and wheel arch and at the leeward A-pillar.

4.4 Data Recording Systems

Aerodynamic forces and moments were recorded using a strain gauged balance purpose built for the crosswind track facility. The 5 component balance can record lift and side force at either axle as well as rolling moment. It is therefore possible to calculate pitch and yawing moments but due to the inertial loads generated by the test equipment it is not possible to measure drag. Balance calibrations were performed at regular intervals throughout the test period and repeated to within 2%.

The balance is interchangeable with a purpose built pressure module of identical dimensions housing 5 Sensor Technics SLP010DD4 differential pressure transducers. The selection and calibration of this transducer is covered in more detail in section 4.7. The specifications and calibration of all data recording equipment is included in appendix B.

Pre-processing of the balance and pressure data is shown in Figure 4-14. The 5 output voltage signals of the balance or pressure transducers pass through hardware filters with cut off frequencies ranging from 151Hz to 164Hz and are then amplified and converted by an acquisition board to a format ready to be downloaded to the PC. The acquisition board can sample at a maximum rate of 5kHz and an accuracy of $\pm 2.5\text{mV}$. The acquisition board has an internal memory of 8192 bits of data that, for example, gives 0.27 seconds of data sampling 6 channels at 5kHz. The acquisition software was developed previously by the Flight Systems and Measurements Laboratory at Cranfield University. Apart from setting data acquisition parameters such as sample rate, trigger setting and number of recordable channels, the software provides a real time display of the 6 data channels when connected directly to the acquisition board. Once run data has been downloaded from the acquisition board, the acquisition parameter values and test data are stored as comma separated variable files ready for further processing.

Flow visualisation of the models was done by painting of the model surface with paraffin paint and also by application of fluorescent tufts. For the surface paint flow visualisation, paint was applied perpendicular to the general flow direction and the wind speed held at 13m/s until the paraffin had evaporated. A picture of each face was then taken with a hand held camera using black and white 35mm film.

Fluorescent tufts were stuck on at 25mm spacings and the tunnel run up to the test speed of 13m/s. The tunnel was blacked out of all natural light and the tufts illuminated using ultra violet strip lamps. The flow over the front, top and leeward faces of the model was then recorded using a super 8 video camera for approximately 10 seconds. Snapshots of the film were then taken using a PC film editor and converted to JPEG picture format. It should be appreciated that the quality of the video film from which flow characteristics are analysed is considerably better than the stills of the film reproduced in chapters 5, 6 and 7.

4.5 Data Reduction

Matlab software had been used previously to process and analyse balance data and the program has been subsequently modified to process and analyse surface static pressure data. The basic function of all data reduction programs for dynamic tests is to:

1. Read the test data as a comma separated variable file
2. Remove wind-off voltage output
3. Calibrate the output voltages to force/pressure data
4. Average 3 runs of data
5. Filter out the track noise signature
6. Subtract wind-off track signature in frequency domain to remove unwanted track oscillations

7. Calculate mean and peak coefficients
8. Translate run data into the position domain using the LED trigger signal

All dynamic test data in the position domain was interpolated every 20mm giving 225 increments of the full run of 4.5m. Data collection is triggered 0.9m before entering the wind tunnel working section and continuously records for the 2.4m gust width and for 1.2m after exiting. All track signatures are presented with distance non-dimensionalised by the gust width, 0 at gust entrance to 1 at exit. The gust is equal to 5 body lengths for all models presented. Mean dynamic coefficients are an average of all dynamic data recorded between 1 and 2m into the gust. This is equal to 2 and 4 body lengths and also equal to 0.4 to 0.8 non-dimensional gust width (x/W). The accuracy of this averaging method is discussed in more detail where results are presented.

For surface static pressure data reduction, the Matlab program also corrected for static pressure variation as described in section 4.1.3 and interpolated and converted data into a format for the Fieldview CFD post processing software package. The pressure data reduction programs also integrated pressures across the model surfaces to estimate aerodynamic forces and moments that are then used as a direct comparison to balance data. The accuracy of integrating pressures to produce aerodynamic forces is discussed in more detail in subsequent chapters.

When completed, the dynamic pressure data reduction program generated a text file containing pressure coefficient information for each tapping location and for each incremental position. A Fortran program then further processed this data to produce a full pressure map of an entire model for each position increment as well as a 10mm grid mesh of the model. Fieldview was then used to bring this data together and to produce an animation of the pressure changes in standard MPEG format.

Data reduction of steady state tests was essentially as those for dynamic but with a 30 second mean taken instead of the position domain calculated average mean. Surface static pressure data contour maps were also produced in a format compatible with Microcal Origin software instead of the animation in Fieldview as described above. Program listings and flow charts showing the detailed data reduction process are included in appendix C.

4.5.1 Calculation of Coefficients

Force data is non-dimensionalised using projected frontal area and by the resultant of the track velocity as measured by the LED sensors and wind tunnel velocity as measured using the Pitot-static probe (Figure 4-2). Additionally, aerodynamic moments are non-dimensionalised by the projected frontal area and overall length. Rolling moments for all models except the Range Rover use square root of frontal area instead of overall length. Flat plate force coefficients use side area and overall length. For the squareback passenger car model, the characteristic length is the wheelbase and characteristic area the projected frontal area of the model. The coefficients are defined as below:

$$\text{Force Coefficient } C_F = \frac{F}{qA}$$

$$\text{Moment Coefficient } C_M = \frac{M}{qAl}$$

$$\text{Pressure Coefficient } C_P = \frac{p - p_\infty}{q}$$

$$\text{where } q = \frac{1}{2} \rho U^2$$

4.5.2 Filter Methodology

Data in its raw state is difficult to analyse because of the unwanted track noise and it is necessary to apply a digital filter before conversion to aerodynamic coefficients. To eliminate track-induced oscillations in the force and moment signatures (pressure data is unaffected), a Matlab program was written to investigate the effect different filter regimes had upon an idealised signal. The chosen Hamming window lowpass filter consists of 2 parts; a pass band and transition band. The stopband is the sum of the two bands and all frequencies above the stopband are eliminated. The frequency content of the signal varies through the transition band from the stopband value to the pass band value, below which all frequencies are retained. Figure 4-15 shows the filter response using a Hamming window with a stopband of 30Hz (the pass band was set at 20Hz and the transition band set at 10Hz). Although the initial peak is diminished it was considered that this filter methodology would yield realistic results. A typical track signature showing data before and after filtering using a Hamming window lowpass filter at 30Hz is shown in Figure 4-16. Before filtering there are large amplitude oscillations in the signal throughout the run and it is difficult to define the gust entrance and exit points. After filtering, the peak on gust entrance can now be seen but the trace still retains some oscillation throughout the run.

A harsher filter could eliminate the lower frequency oscillation and the stopband was then set at 20Hz and is included in Figure 4-15. At 20Hz, the trend of the signal is unaffected but the nature of filtering a discrete signal with a fast Fourier transform induces oscillations at abrupt changes in magnitude and a noticeable loss in peak response. Hanning and Blackman windows were subsequently investigated but did not yield a significant improvement.

Figure 4-17 and Table 4-1 shows the effects of various filter regimes on the side force coefficient of a single run of the flat plate model at 13.5m/s track speed and approximately 30° yaw. It can be seen from Figure 4-17 that the selected filter of 30Hz gives negligible reduction in both mean and peak response. However, the effect of filter settings on the mean and peak yawing moment coefficient is more severe. Table 4-1 shows that a lowpass filter setting of 50Hz gives a 0.11 increase in the peak yawing moment coefficient when compared to the selected filter of 30Hz. From this analysis, it is apparent that the transient

peak on entering the gust could be either an aerodynamic effect or a function of track noise. This problem can also be extended to the general oscillations found in the track signatures, it is uncertain if these are aerodynamic in nature or functions of track noise. To counter this problem, Macklin³ removed the wind-off track signature (i.e. zero yaw) from all other track signatures so that values are relative to the zero yaw case. This method of reducing data is shown in Figure 4-18. Whilst generally valid for low angles of yaw, it was found that the track signature alters with increased yaw. This was attributed to the wind-on side force damping out track induced oscillations as the side force increased. As a result little confidence could be had in the aerodynamic coefficients calculated by this method and the error was such that for certain coefficients at low angles of yaw, the wind-off signal was greater than the wind-on. A further problem was that the wind-off track signature was subtracted in the position domain and because the excitation of track noise does not necessarily occur at the same point the subtraction of a wind-off track signature would corrupt the results. The principal of superposition as used then actually causes a negative oscillation in the wind-on signature rather than eliminates it and is schematically shown in Figure 4-19. To solve this problem, the subtraction of wind-off track signature has now been performed in the frequency domain before filtering of the raw data signal. The track-induced frequencies are then eliminated at low angles of yaw but only partially at increased values due to the crosswind gust damping effect mentioned above.

After the above investigation, it was considered that digital filtering was optimised to reduce track-induced noise without corrupting the aerodynamic signal, and for all subsequent filtering, a low pass Hamming window filter was set at 30Hz. The lesson learned from the above investigation into filter methodology is that great care must be taken in interpreting the force and moment dynamic traces. For all results presented in this thesis, data has often been processed with various filter settings and sets of data are repeated with different experimental set-ups, for example, the 2-box model was tested at 3 different weights to try and eliminate the track induced vibrations. In addition, all datasets are analysed using a variety of different averaging and processing techniques. This has been done to ascertain if the oscillations in the dynamic traces are aerodynamic in nature or a vibration frequency originating from the test equipment.

Table 4-1 Effects of Various Filter Regimes on Mean and Peak Coefficients

<i>Stopband (Hz)</i>	<i>Pass band (Hz)</i>	<i>Trans Band (Hz)</i>	<i>Mean Cs</i>	<i>stdev Cs</i>	<i>peak Cs</i>	<i>Mean Cy</i>	<i>stdev Cy</i>	<i>peak Cy</i>
130	100	30	1.34	0.14	1.67	0.15	0.14	0.38
50	40	10	1.34	0.10	1.65	0.15	0.14	0.40
40	30	10	1.33	0.08	1.65	0.16	0.08	0.29
35	25	10	1.33	0.07	1.65	0.17	0.02	0.21
30	20	10	1.33	0.08	1.62	0.17	0.01	0.19
25	20	5	1.33	0.11	1.58	0.17	0.01	0.19
25	15	10	1.31	0.07	1.46	0.17	0.01	0.19
20	15	5	1.30	0.11	1.38	0.17	0.01	0.19
20	10	10	1.30	0.05	1.31	0.17	0.00	0.19

4.6 Data Accuracy and Repeatability

It has been shown that the improved simulation gained by dynamic testing results in a loss of measurement accuracy. Stewart⁵² estimated a loss of accuracy of between 10 and 15% over conventional wind tunnel tests. For this investigation, small changes in coefficients need to be measured and therefore a stringent test regime was required to have confidence in the final data.

The measurement of the basic test parameters such as ambient temperature, ambient pressure, model carriage velocity and wind tunnel velocity is a possible source of inaccuracy. In a previous investigation using the same equipment, Macklin³ investigated what affect these airflow parameters had upon the final data points. It was found that measurement of the track velocity caused the greatest inaccuracy at small values of yaw. With a measured deviation of track speed of ± 0.04 m/s the error in yaw coefficient was 0.004, which though well within the limits of resolution required represents an error of almost 20%. It is thought that this inaccuracy was due to incorrect measurement of the trigger LED's along the side of the track that has since been rectified. Another inaccuracy was that of the measurement of balance voltage at small values of yaw and the calculated error was 0.003.

Another possible source of error is blockage of fluid flow as the model traverses the wind tunnel working section. To account for the effect of blockage in the working section the method of continuity as recommended by the SAE⁵³ can be used to correct the force, moment and pressure coefficients. The corrected dynamic pressure is:

$$\frac{q}{q_c} = \left[1 - \frac{S}{C} \right]^{-2}$$

Where q_c is the corrected dynamic pressure, q is the uncorrected dynamic pressure, S is the duplex model area and C is the duplex test section area. The corrected pressure coefficient is then:

$$C_p = 1 - \frac{(1 - C_{PU})}{\left(\frac{q_c}{q} \right)}$$

Where C_{PU} is the uncorrected pressure coefficient.

For this research it is difficult to apply an equivalent blockage correction for both steady state and dynamic test methods. Static pressure variation is inconsistent between each method and it is uncertain how to account for the slot flow during dynamic tests. In addition, a blockage correction applied to steady state data based on projected frontal area will have a different reference area during dynamic tests.

52. Stewart M J, Transient Aerodynamic Forces on Simple Road Vehicle Shapes in Simulated Crosswind Gusts, Mira 1977/5

53. Closed-Test-Section Wind Tunnel Blockage Corrections for Road Vehicles, SAE SP - 1176, 1996

In the case of steady state flat plate tests, which represented the greatest blockage of models tested in this research, the blockage correction calculated by the above method was never greater than 2%. This is a small blockage and in light of the uncertainty of applying a blockage correction to dynamic data, no blockage correction has been applied to any of the final data presented in this thesis.

In a previous investigation, Macklin³ found that all coefficients were Reynolds number dependent above values of 4×10^5 and for comparative force data tests (Appendix A), squareback passenger car data was collected under the same conditions. Reynolds number dependency for other model configurations is discussed in the relevant chapter.

4.6.1 Accuracy of Measured Pressures

The fluid pressure on the surface of an object can be sensed by small holes (tappings) drilled in the surface of a flow boundary in such a way that flow stagnates so rapidly in the region of the sensing holes that heat transfer and frictional effects can be neglected. This in theory can be sensed by a small hole on the boundary of the fluid flow. The smaller the hole diameter the slower the response to a pressure change.

Pressure tapping errors are dependent on hole geometry and shape. For square edged holes, the streamlines separate cleanly at the upstream edge and the fluid flow is relatively undisturbed. However, viscosity effects cause a slight forward motion to be imparted to the fluid in the hole resulting in a small positive error. Fluid flow over round holes does not immediately separate but instead is guided into the tapping resulting in a portion of the dynamic pressure being measured and a positive error. Wall geometry to reduce error for round holes as recommended by Benedict⁵⁴ is shown in Figure 4-20. A countersunk hole causes clean separation at the upstream edge but local acceleration of the fluid at the downstream edge resulting in a suction action and a slight negative error.

Pressure tapping errors occur because of a local disturbance in the boundary layer and are usually related to a function of the wall shear stress since it characterises the local velocity gradient. As a general rule, wall shear stresses are roughly 1% of the freestream dynamic pressure⁵⁵ and thus the change in measured pressure coefficient will be of this order.

The stagnation pressure coefficient is generally accepted as having the value of 1 for usual applications. However, it is highly dependent on Reynolds number based on outside diameter of the tapping and consequently viscous effects of the fluid. Tritton⁵⁶ shows that at $Re > 1000$ C_p can be taken as 1, for $50 < Re < 1000$, the C_p falls to between 0.99 and 1 and if $Re < 10$ the C_p is always greater than 1 and rapidly rises to the asymptotic value of $5.6/Re$. The Reynolds

54. Benedict R P, Fundamentals of Temperature, Pressure and Flow Measurements 3rd ed., pp. 265- 293, John Wiley 1984

55. Panton R L, Incompressible Flow, pp. 132-138, ISBN 0471897655, John Wiley 1984

56. Tritton D J, Physical Fluid Dynamics, pp. 70-82, 2nd ed. , Oxford Science 1988

number based on pressure tapings used in this research is much greater than critical and thus the stagnation pressure coefficient can be taken as 1.

4.7 Development of Dynamic Pressure Measurement System

A pressure sensing system involves small pressure holes flush to the model surface that open to tubing of small diameter, which are then connected to a transducer. In the case of the crosswind track the pressures are time varying, there is fluid flow along the tubing and consequently a fluid flow resistance. This tubing resistance causes the pressure signal at the transducer to lag the actual pressure at the orifice. The model takes approximately 120ms to traverse across the crosswind gust and it was immediately apparent that the response time of the pressure transducer was critical for this application. Apart from the response characteristics of the transducer itself, Benedict⁵⁴ shows that response time in transient pressure measurement utilising tubing is reduced with:

- Large tubing diameter
- Small system volume
- Increased applied pressure to be measured
- Small tubing length

For this system the measured pressures are extremely small with a maximum applied pressure of only 480Pa and a minimum of 10Pa. In addition, the transducer has to be remote from the measurement tapping and various tubing lengths up to 450mm need to be utilised. In fact, all the requirements for a low response time have been broken and the calculated response time from equations presented in Bynum⁵⁷ is of the order of 10 times greater than the time it takes to traverse the tunnel. Benedict⁵⁴ presents alternative equations to calculate this lag in response and for the crosswind track using a 400mm length of tubing the pressure lag time is calculated as 0.3s, but this is again greater than the time frame considered.

It is acknowledged that the calculation of response times by these equations is not accurate for all configurations and especially when the internal volume is small, as is the case here. Also, initial tests showed that the selected pressure transducer responded to the transient crosswind gust and further tests would be needed to clarify transducer performance.

In addition to a pressure lag, transient pressure measurement on the crosswind track raises two problems:

- What can we use as reference pressure?
- What are the effects of inertial loading on the measurement system?

These problems will now be considered in turn.

57. Bynum D S, Wind Tunnel Pressure Measuring Techniques, Agardagraph AG-145-70, 1970

4.7.1 Selection of Reference Pressure

One of the greatest problems that had to be overcome for the dynamic pressure measurement system was the selection of a moving reference pressure to the measuring port of the transducer that was known to be consistent.

There were several options:

- *Reference to a moving static probe.* The first option was to use a static probe placed on the model carriage beneath the groundboard so that the reference pressure should not be affected at different values of yaw. The drawbacks of this reference pressure method were that the probe alignment is not exact and it was hard to distinguish between the true static pressure value of the moving carriage and other effects due to flow blockage caused by objects beneath the working section of the wind tunnel.
- *Reference to atmospheric.* A second possibility was to use a long piece of tubing to connect the reference port to atmospheric and let it trail behind the model carriage. This idea was rejected because of the need to modify the track so that the trailing tube would not get caught up in the firing mechanism.
- *Seal the reference port at atmospheric.* In this method, a valve was connected to the reference port and instantaneously closed at atmospheric pressure immediately before tests. This initially suffered from drift problems as shown in Figure 4-21. The figure shows an average of three runs at approx. 12.5m/s track speed and the tunnel speed at approx. 7.5m/s giving a yaw angle of 30 degrees. Even with the inertial track signature removed there is clearly still drift representing 0.1 of a pressure coefficient between the entry and exit points of the wind tunnel. A temperature difference in the connecting tubing was eventually identified as the cause of this drift, internal tube volume being so small that the slightest temperature difference caused a pressure change within the tubes. The solution was to use a thermos flask as an insulated reservoir which when applied gave a very stable reference pressure.

The disadvantage of this system was that pressures had to be recorded referenced to atmospheric instead of the wind tunnel static pressure and would have to be accounted for in the subsequent data analysis. A survey of wind tunnel static pressure across the crosswind gust over a range of tunnel speeds showed that static pressure was proportional to the wind tunnel dynamic pressure. Consequently, the difference between atmospheric and wind tunnel static pressure can be represented by a pressure coefficient offset as described in section 4.1.3.

4.7.2 Inertial Loading on the Crosswind Track

The crosswind track model travels at speeds up to 20 m/s and experiences large inertial forces during acceleration and braking. Any pressure system has to be located on the track and as such is subject to the same inertial forces.

If we consider the tubing to be 400mm long and of internal diameter 2mm, the internal volume of the transducer to be approximately 10mm^3 and the density of air to be 1.225kg/m^3 , then the mass of air within the tubing system will be 1.54mg. Additionally, if the acceleration of the carriage is assumed to be instantaneous and equal to the worst case of 20m/s^2 , then the force applied to the transducer diaphragm will be approx. $3 \times 10^{-5}\text{ N}$. If the diaphragm area is assumed to be approx. 25mm^2 , then the applied pressure due to inertial loading can be calculated as 1.23Pa. This applied pressure due to inertial loading is negligible even at the low pressures measured (approx. 100Pa) and the tubing system can be considered to be insensitive to the inertial loading of the crosswind track. Further to this, the calculation assumes the worst case scenario with the transducer diaphragm and tubing to be orientated along the accelerative axis. If the orientation is aligned normal to this axis the inertial loading will be practically zero.

4.7.3 Pressure Transducer Selection

The College of Aeronautics already has an existing pressure transducer previously used to measure the pressures on the ground plane beneath a moving vehicle⁵⁹. The transducer is model SLP010DD4 made by Sensor Technics and the technical specifications of this differential variable resistance strain gauge transducer are shown in appendix B. The advantages of the transducer are its low cost, low noise and ability to measure low pressures. A disadvantage already noticed was that the transducer is very sensitive to changes in temperature. This was not seen as a great problem since zero readings are performed for each run of test data.

The maximum expected pressure around the model during dynamic tests would be at the tunnel speed required to give the maximum yaw angle of 25° . If the track speed were set at 13m/s, this would give a resultant dynamic pressure of 135 Pa. This represented 5% of the full-scale span of the SLP010DD4 at 2560 Pa.

The SLP010DD4 is specified as having a typical sensitivity of 0.85mV/V/inch water. For a supply voltage of 6V and a minimum pressure of 256 Pa, the output voltage will then be 5.1 mV. To present data on a $\pm 5\text{V}$ range a gain of 980 (5/0.0051) was needed. The transducer is completely linear through its range i.e. if there is a pressure change there will be a change in output voltage and the limitations of resolution were then determined by noise, typically 0.01mV ⁵⁸, and losses in filtering and amplification. The acquisition board resolution is 2.44mV and one increment change at 20m/s represented a change in pressure coefficient of 0.007. With an increase of the resultant speed of the crosswind gust this resolution is further improved to a 0.004 change in pressure coefficient.

Normally, vibration and inertial loading are not considered critical in pressure measurement. However, due to the dynamic nature of the test equipment a check was needed on the operating range of the transducer. Vibration will occur

58. Private Communication, Tony Harris, Sensor Technics, July 1997

due to the track noise and the large inertial loads experienced during acceleration and braking. The SLP010DD4 casing was liable to burst and the sensing element damaged if the pressure exceeded 150 inches of water (37kPa). A simple calculation based on deceleration of the transducer internal volume showed that the inertial loads during braking (deemed to be the worst case) would be considerably less than this and, if the sensor was aligned normal to this axis the inertial load would be zero.

Ringling of the transducer dependent on its resonant frequency may also occur at the starting shock of entering the tunnel. Previous tests by Pillard⁵⁹ using the same transducer showed that the resonant frequency of the transducer was approximately 350Hz. This was too high for this application and the low pass hardware filters that have cut off frequencies of 160Hz will remove any ringing.

The temperature operating range of the SLP010DD4 is -20 to 50°C and was well within the operating conditions. However, one concern initially noticed during calibration was the sensitivity of the transducer to differences in ambient air temperature in the immediate vicinity of the transducer and also in the connecting tubes from the transducer to the measurement port. Several sources of temperature difference could occur during the operation of the equipment. Foremost is from the wind cooling effect as the transducer traveled along the track and secondly, the signal conditioning equipment in the immediate vicinity of the transducer could cause local temperature differences. For these reasons the transducer needed to be well insulated from its external surroundings.

Sensor Technics also produced a more sensitive version of the SLP010DD4 that had a range of 0 to 4 inches of water (SLP004D). Additionally the transducer could be purchased temperature compensated and calibrated (SCXL004DN) but at an increase in cost. A further transducer considered was the 103LP05D-PCB also by Sensor Technics with a range of 0 to 2 inches of water and which came temperature compensated and calibrated and also included signal conditioning circuitry. Although more suited for our purpose using the above transducers all meant an increase in expenditure. It had to be considered that at this initial stage, the effects of the dynamic nature of the track were as yet unknown and that the SLP010DD4 provided the most cost-effective solution.

The suitability of the SLP010DD4 transducer for pressure measurement under transient dynamic loading was determined from the following series of tests:

1. Influence of Pressure Tapping and Tube Geometry
2. Influence of Tubing Length
3. Influence of Transducer and Tube Orientation
4. Frequency Response Characteristics

Which will now be considered in turn.

59. Pillard S, Measurement of Pressure Data Beneath a Moving Vehicle, MSc Thesis, Cranfield University 1997

4.7.3.1 The Influence of Pressure Tapping and Tube Geometry

Different pressure tapping configurations were used to investigate changes in pressures from differing pressure tapping systems. A total of 4 configurations which complied to the recommended tapping geometry of Benedict⁵⁴ (Figure 4-20) were made to connect with the following tubes:

- Green 1.1mm internal diameter.
- Brown 1.7mm internal diameter
- Blue 2.1mm internal diameter
- Clear 2.9mm internal diameter

All tubes were 10cm long and connected to a Sensor Technics SLP010DD4 low pressure transducer and for each configuration 3 wind-off runs at a track speed of approximately 13.5m/s were recorded.

The pressure coefficient dynamic traces for the 3 runs of each tube configuration are shown in Figure 4-22. It was expected that the greatest difference in mean and peak response would be between the green and clear tubing configurations since this represented the greatest difference in tubing configurations. However, Figure 4-22 does not show this to be the case and there is no correlation between any of the different tubing configurations. All configurations give good repeatability especially if it is considered that for the zero yaw angle the resultant dynamic pressure is very low at only 110Pa. This represents only 4% of the full-scale span of the SLP010DD4 transducer and it is anticipated that wind-on data would further improve track signature repeatability.

The anomaly in data between 0 and 0.5m in the dynamic traces is unexpected. All runs are conducted wind-off and in theory the dynamic traces should be an approximate horizontal line with no large deviations. The rise at 0 to 0.5m is attributed to the change in pressure as the model passes from open air to above the groundboard. It can be concluded from this series of tests that the measured pressures appear to be insensitive to tapping and tube geometry.

4.7.3.2 The Influence of Tubing Length

A series of wind-on tests at a single tapping were conducted with 4 different tubing lengths (400, 300, 200 and 100mm). Dynamic traces are shown in Figure 4-23 and it can be seen that tubing length has no effect upon peak or mean pressure response. It is also noted that rise time is also unaffected with increased tube length.

The anomaly in data found in the wind-on tests at 0 to 0.5m where the model carriage passes the groundboard is still present but now the steady state value is reached within 0.3m. Since the tubing configuration is the same for both wind-on and wind-off tests, the quicker response time for the wind-on tests can only be explained because the change in measured pressure is greater. This implies that there is a change in pressure outside of the wind tunnel working section

when the wind is on and is coincident with the development of a pressure gradient through the gaps in the working section to allow passage of the model. The pressure gradient is obtained from the static survey described in section 4.1.3 and a correction based on this pressure change is accounted for in subsequent data reduction programs. The single conclusion from this series of tests was that response of the dynamic pressure system is insensitive to tubing length within the range tested.

4.7.3.3 The Influence of Transducer and Tube Orientation

This set of tests aimed to determine the inertial sensitivity of the SLP010DD4 transducer during dynamic tests. For the tests, the transducer was set up as described in section 4.4 and the measurement port connecting to a tapping on the windward side of the flat plate model. The track speed was constant at approx. 18m/s and all the tests were conducted with wind-off. The data acquisition system was set up so that sampling was triggered by a keyboard strike and the model then fired so that the inertial loading from the at rest to stopped position could be plotted. Two different orientations of tubing were tested: normal and parallel to the track direction and 4 different lengths of tubing were used: 100mm, 150mm, 200mm and 250mm. A control configuration with no tubing and both ports open to atmospheric was also recorded. In theory the worst case orientation for the transducer itself is when the diaphragm is normal to the track velocity. The inertial loading in the other two planes with the transducer parallel to track direction should be of equal magnitude and close to zero and this configuration was used for the subsequent tests.

For the control configuration the increase in output due to dynamic loading was negligible. No correlation could be made between the tube length and increase in inertial loading at either orientation. Additionally, the inertial loading when the tubing was placed parallel to the track velocity (deemed to be the worst case) could not be said to be any worse than when the tubing was normal to the track velocity. The deviation of all configurations tried did not differ more than 0.1V from the control configuration and at this track speed represents 0.03 of a pressure coefficient. The conclusions from this test were:

- The inertial loading can be kept to a minimum by keeping the diaphragm of the transducer parallel to the track direction.
- The length and orientation of tubing used to connect the pressure transducer to the measurement tapping has little effect on the measured pressures when subjected to the inertial loads of the crosswind track.

4.7.3.4 Frequency Response Characteristics of the SLP010DD4 Pressure Transducer

During this series of tests, the experimental apparatus was set up as in Figure 4-24. The flat plate model as described in section 4.3.1 was placed flush to a low frequency speaker and clamped to a workbench to give an airtight seal. The speaker was then excited by an amplified sine wave from a variable frequency function generator. A reference pressure tapping was drilled in the model

surface and connected via a 20mm length tube to an SLP010DD4 transducer. This is the reference transducer and measures the instantaneous pressure at the model surface, an assumption not strictly true because of the small connecting tubing but was expected to be within the limits of experimental error. A second SLP010DD4 transducer was connected via different tubing lengths to the test tapping. Data was collected using the crosswind track data acquisition equipment at 500Hz for approximately 8 seconds and 5 tube lengths (200mm, 250mm, 300mm, 350mm and 400mm) were tested at frequencies of 1 to 100Hz.

Processing of the frequency data begins by removing the initial zero offset and then calibrating the two channels to pressures (Pa). A fast Fourier transform is applied to the reference and test data and the complex frequency response transfer function calculated as:

$$H(s) = \text{Input}(s)/\text{output}(s)$$

Phase difference and amplitude ratio for each frequency and test tubing length is then determined and are shown in Figure 4-25 and Figure 4-26. It can be seen that the tubing length has a considerable effect on the frequency response of the pressure measurement system at higher frequencies. For an excitation frequency of 100Hz and tubing length of 450mm, the output pressures are approximately half the magnitude at the measurement tapping and over 50 degrees out of phase. However, the frequencies of interest for the analysis of transient crosswind data are much lower at approximately 20Hz and as such represent an amplitude ratio error of less than 3% even for the longest tubing configuration. Resonance of the transducer and tube system does not occur within the measured limit of 100Hz.

In a previous investigation by Sims-Williams⁶⁰, the author describes how the calculated transfer function can now be used to correct frequency domain data and so correct for the effect tube length damping has upon the measured amplitude and phase. A similar method is incorporated into the data reduction by Matlab programs described in section 4.5.

4.8 Conclusions

The chapter has described the Cranfield crosswind track facility and experimental arrangement used in the present investigation. Track improvements to ensure data repeatability have been described. The detailed testing and analysis of data obtained using the Sensor Technics SLP010DD4 pressure transducer shows that the transducer is appropriate for the dynamic testing of this investigation.

60. Sims-Williams D B and Dominy R G, Experimental Investigation into Unsteadiness and Instability in Passenger Car Aerodynamics, SAE 980391, 1998

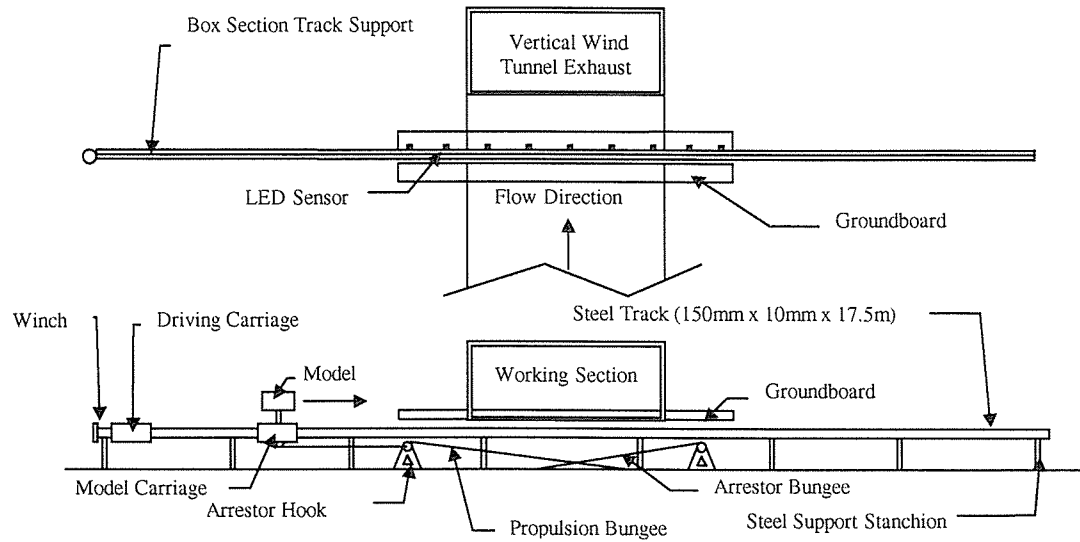


Figure 4-1 The Crosswind Track Facility and 2.4m x 1.2m Wind Tunnel

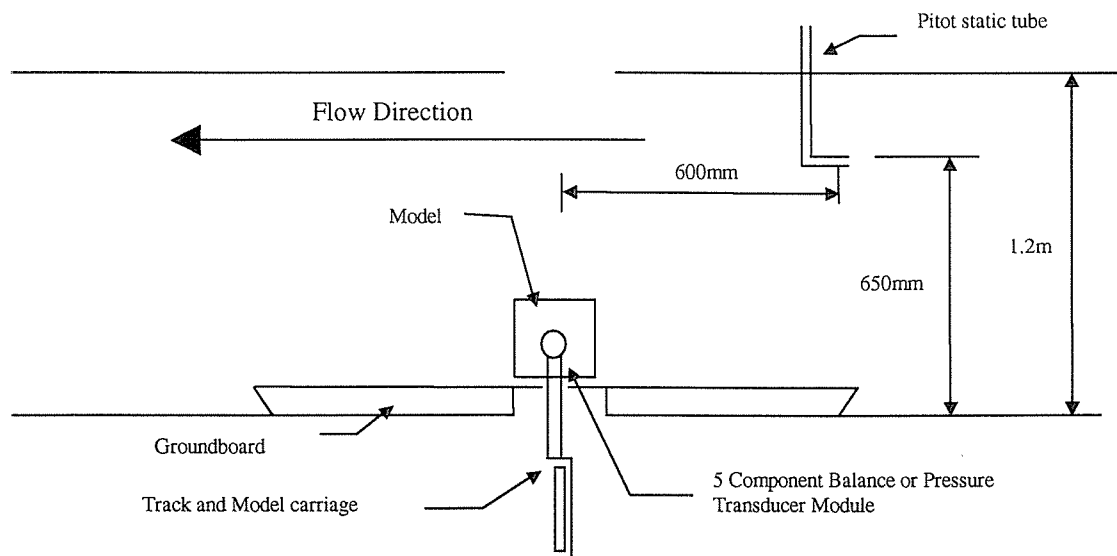


Figure 4-2 Cross section of Crosswind Track Facility

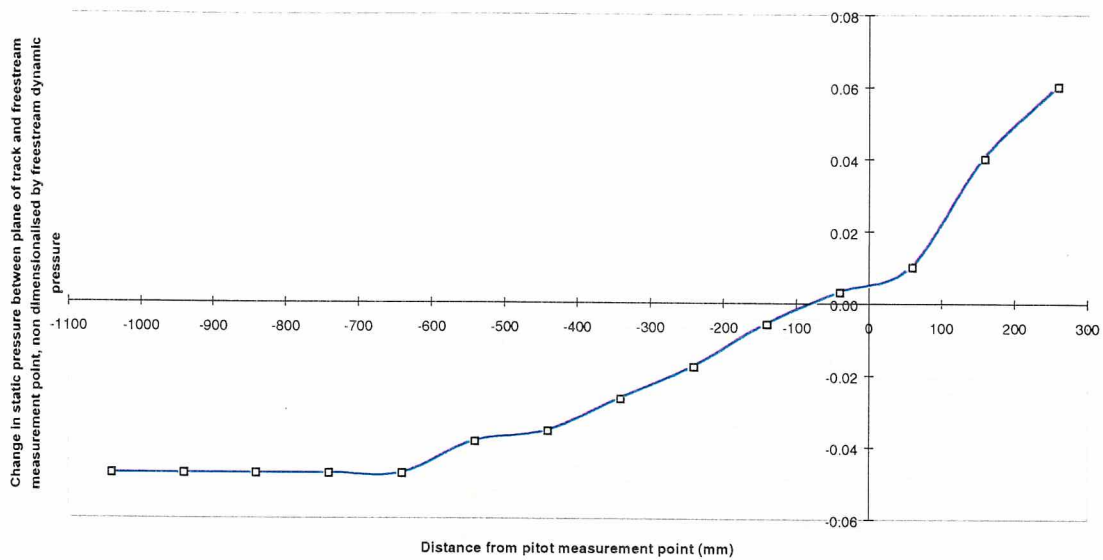


Figure 4-3 Static Pressure Variation along the Groundboard

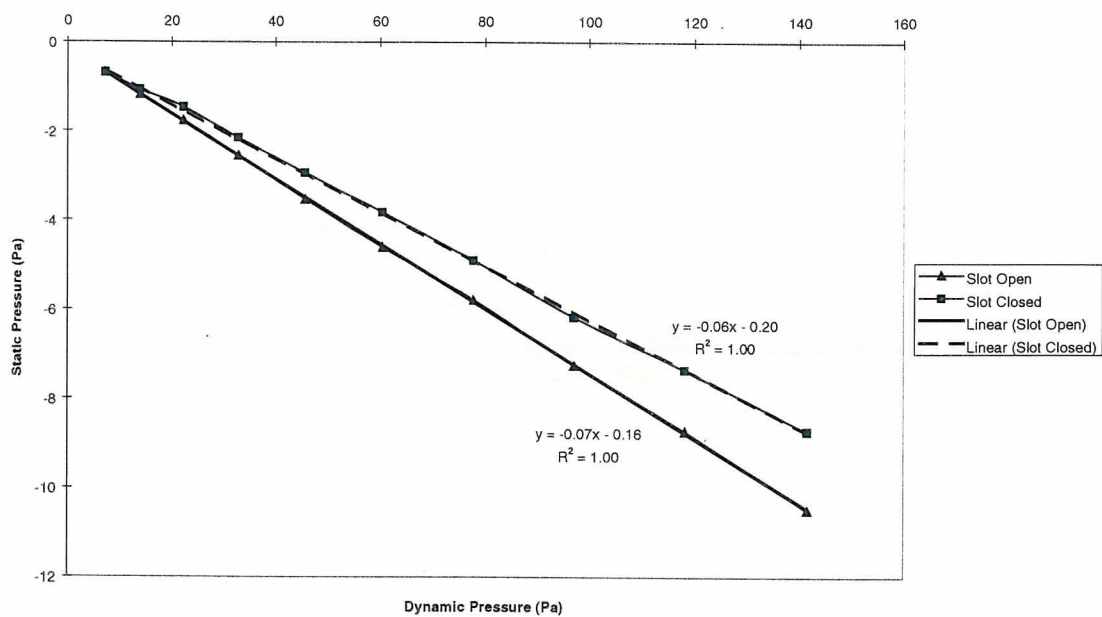


Figure 4-4 Change in Static Pressure against Dynamic Pressure

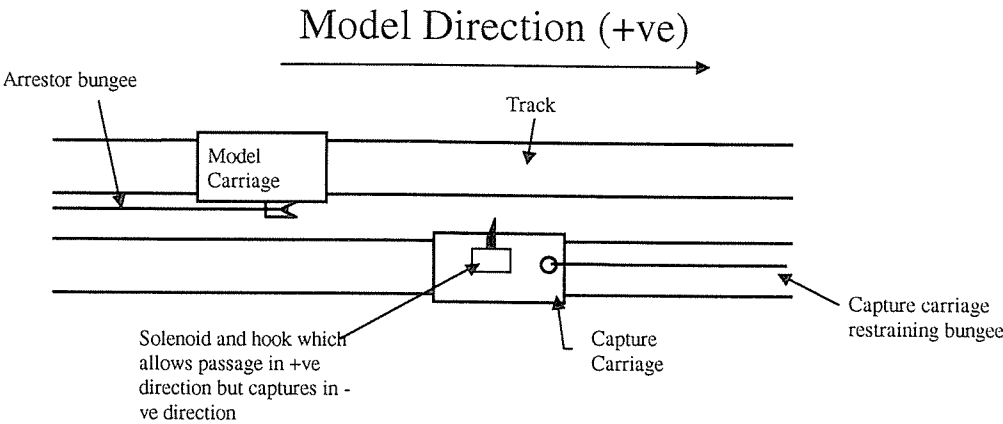


Figure 4-5 New Model Carriage Return Mechanism

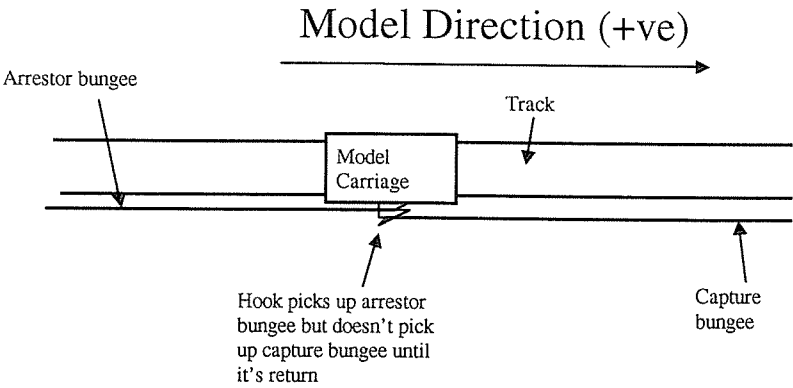


Figure 4-6 Modified Model Carriage Return Mechanism

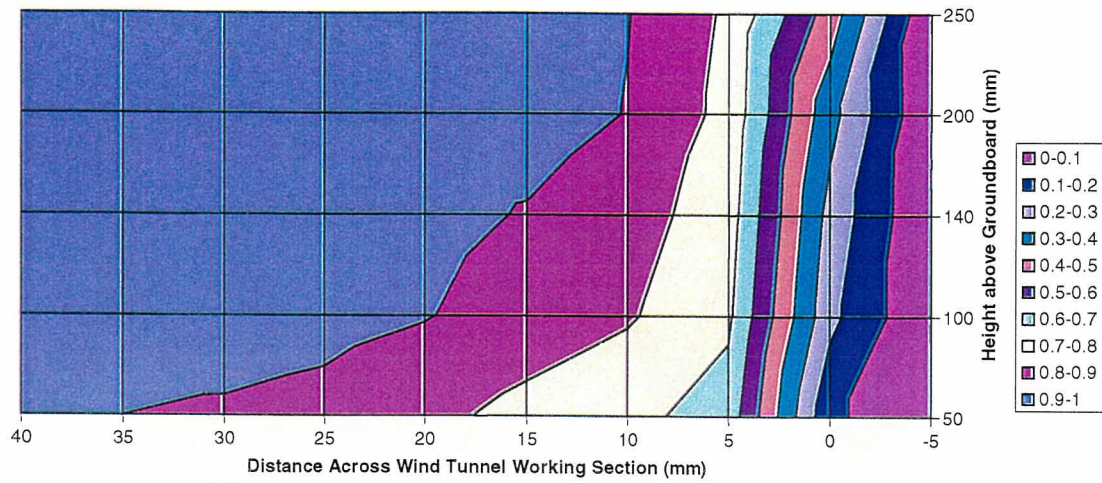


Figure 4-7 Dynamic Pressure Variations across the Wind Tunnel Working Section

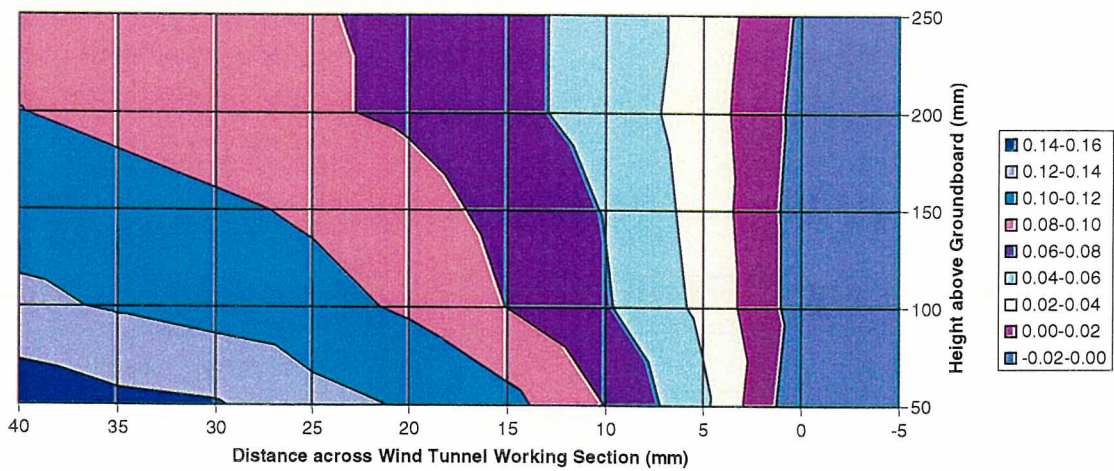


Figure 4-8 Static Pressure Variations across the Wind Tunnel Working Section

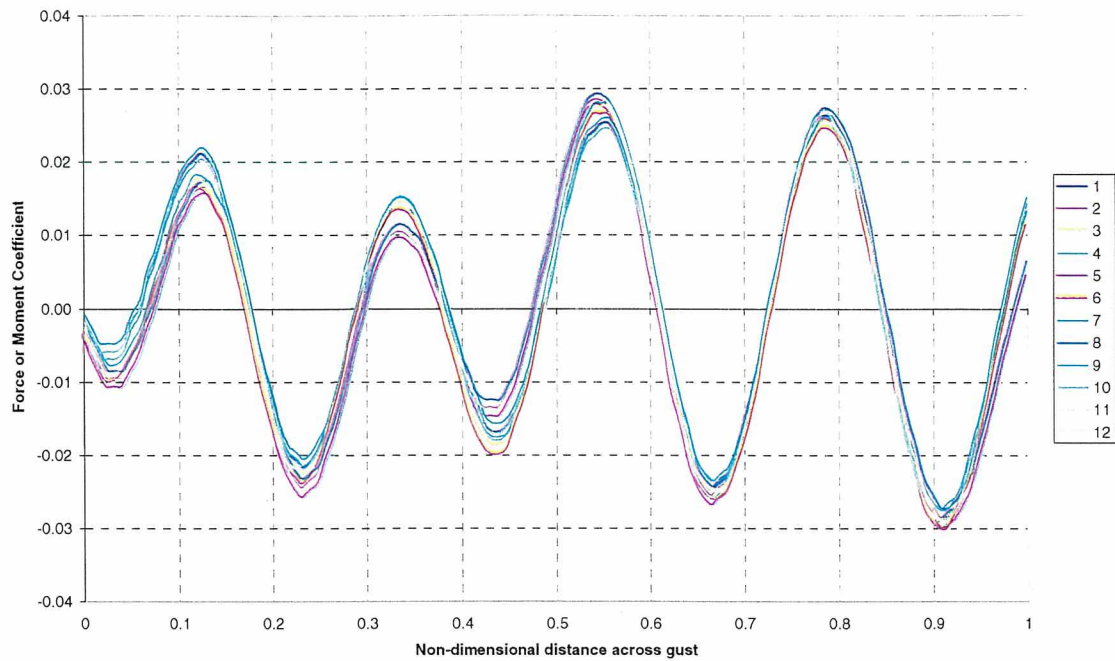


Figure 4-9 Repeatability of Wind-off Track Signatures (12 Runs)

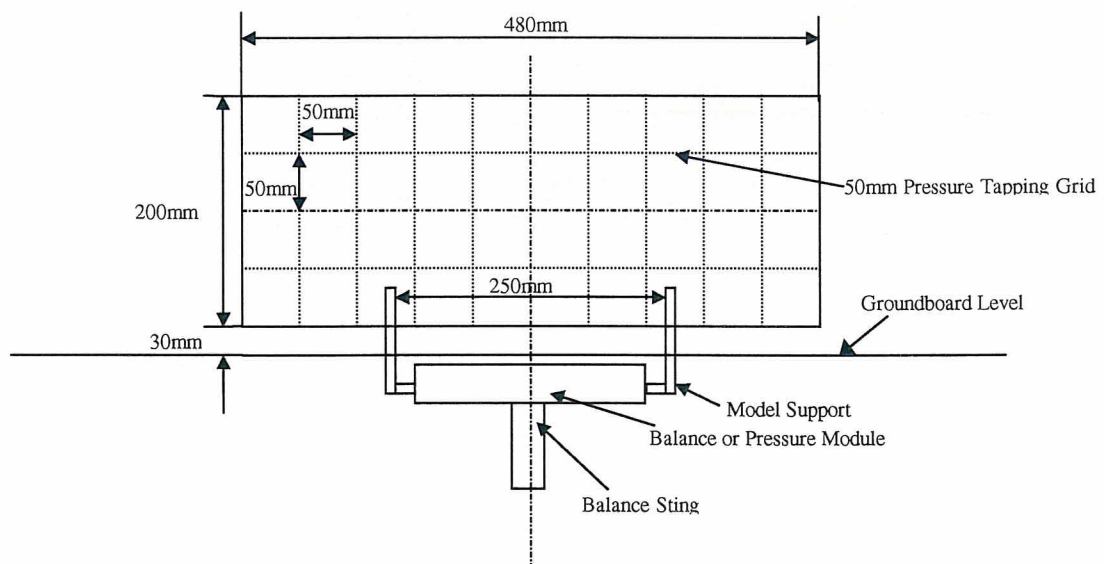


Figure 4-10 Flat Plate Model Showing Tapping Positions and Model Supports

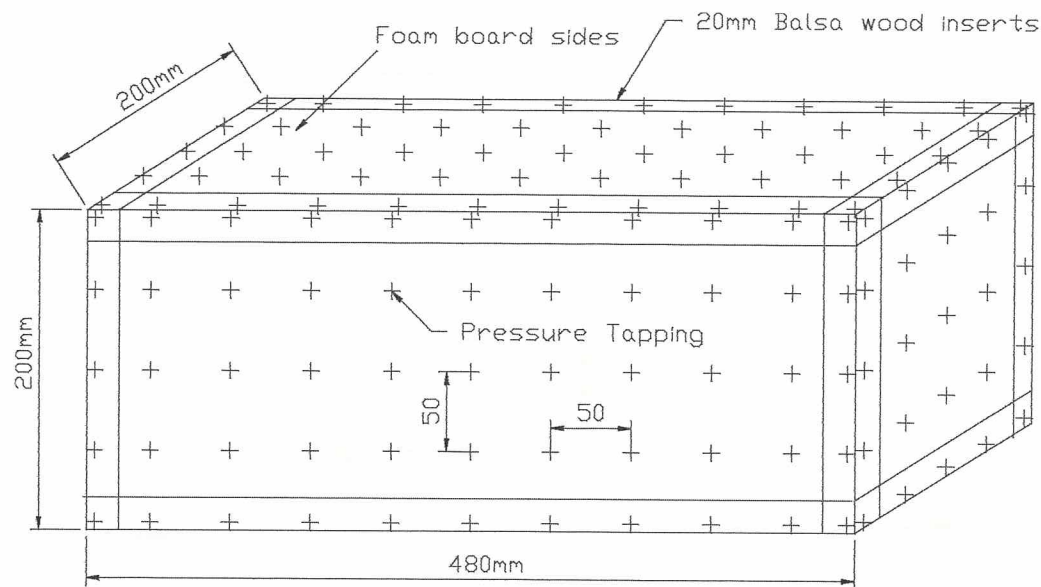


Figure 4-11 Exterior Dimensions and Pressure Tapping Locations of 1-Box Model

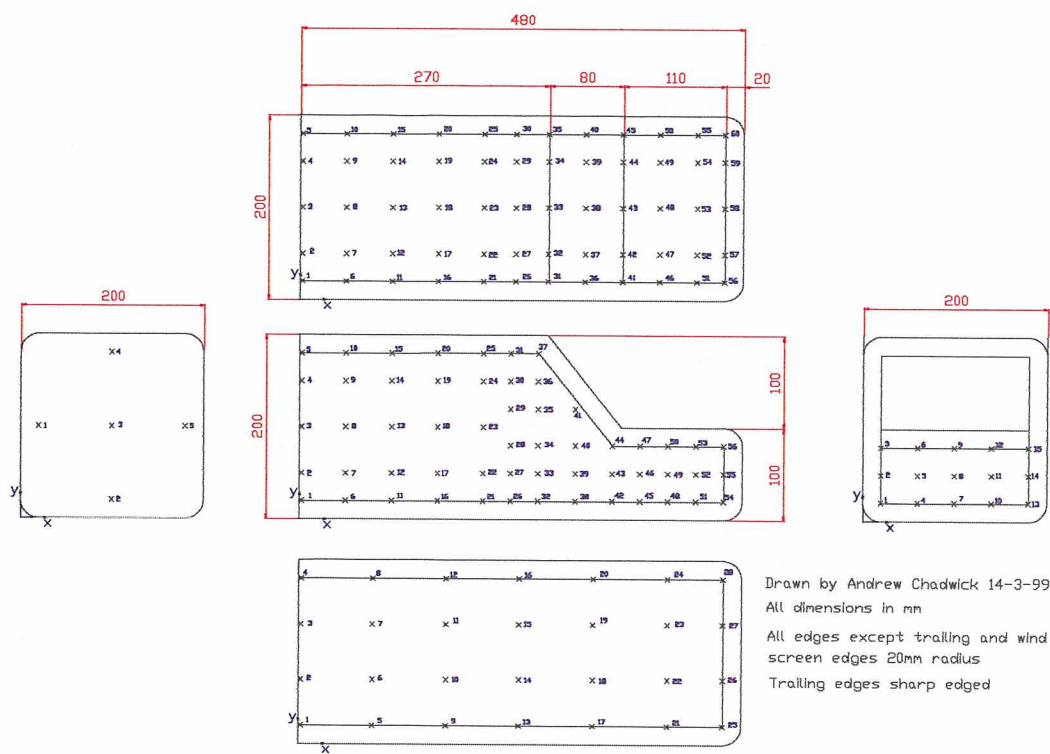


Figure 4-12 Exterior Dimensions and Pressure Tapping Locations of 2-Box Model

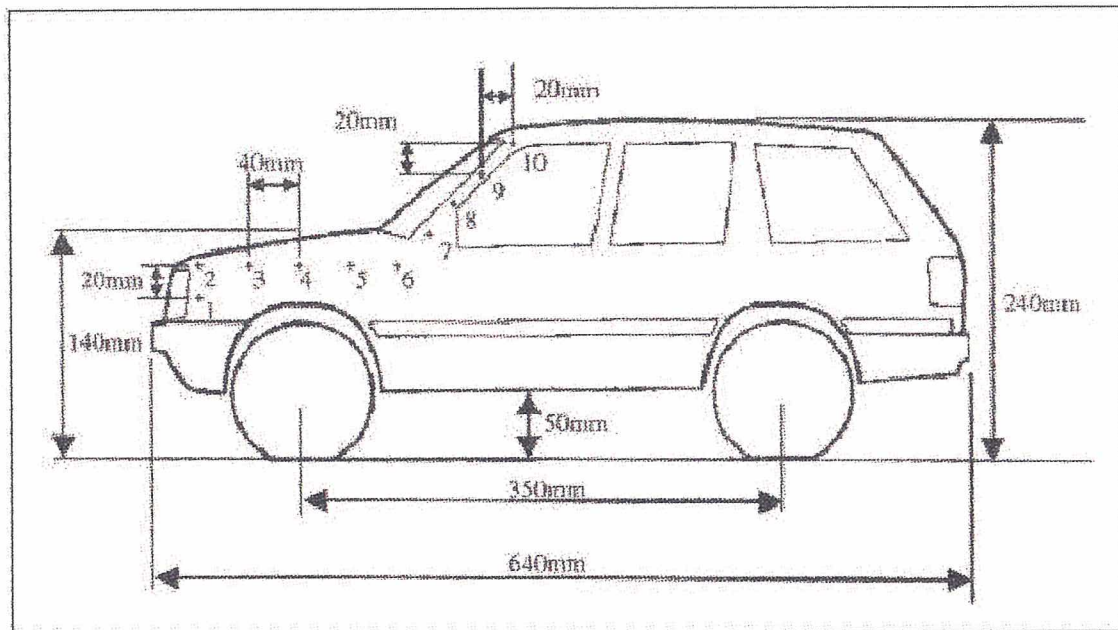


Figure 4-13 Exterior Dimensions and Pressure Tapping Locations of Range Rover Model

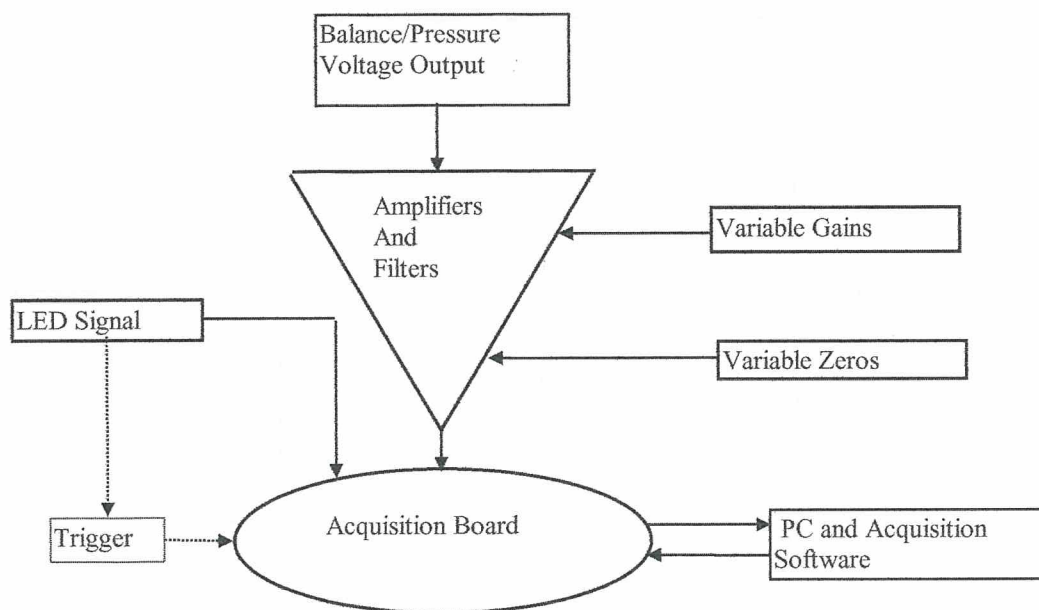


Figure 4-14 Output Signal Pre-processing. After Macklin³

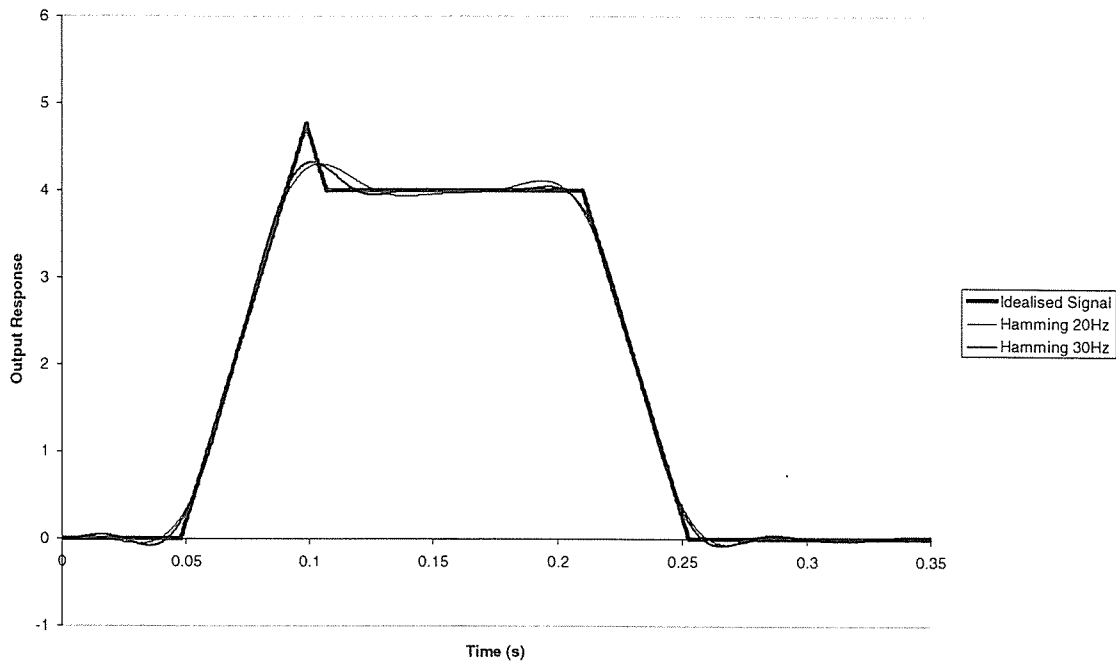


Figure 4-15 Idealised Signal and various Hamming Window Filters

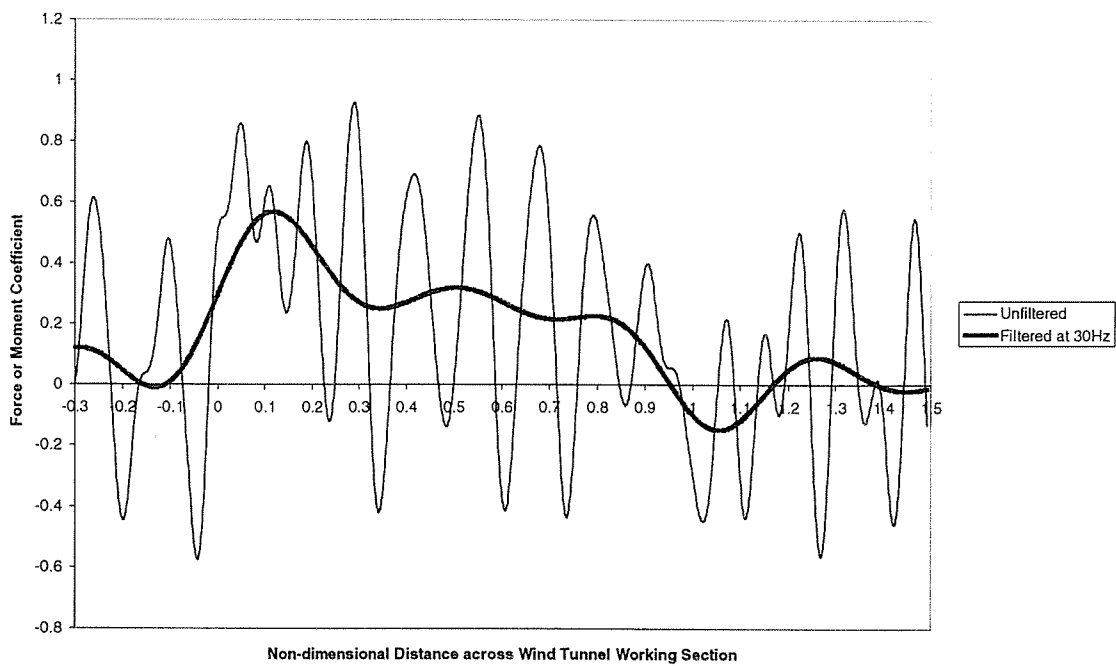


Figure 4-16 Typical Track Signature Showing Removal of Noise by the Selected Filter

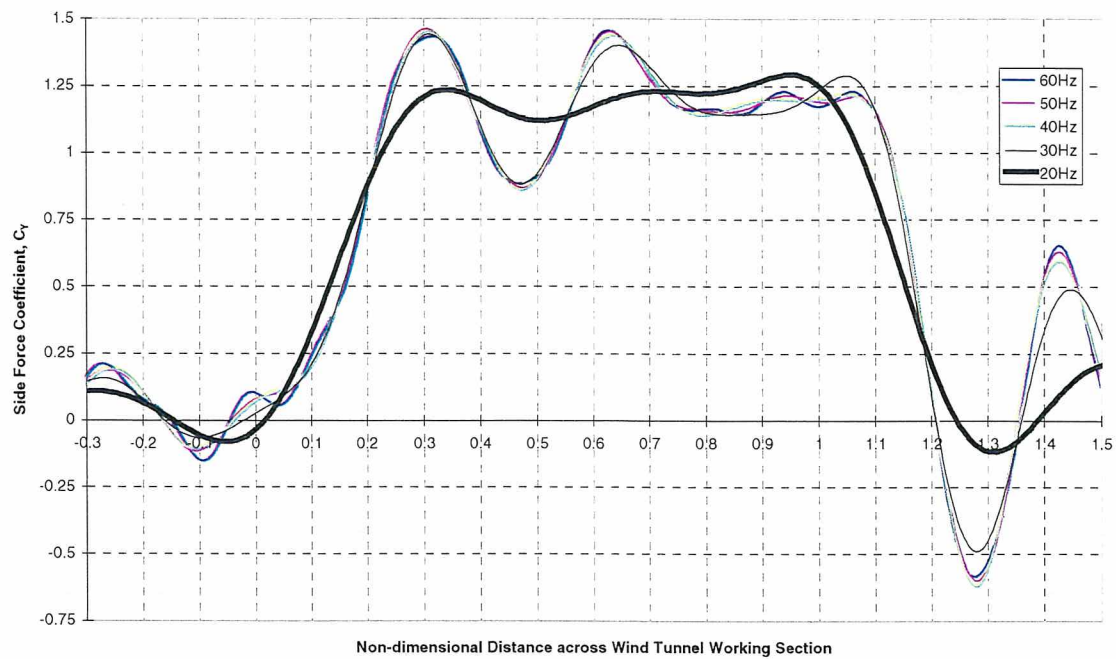


Figure 4-17 Track Signatures for 30° Yaw Case with Various Lowpass Filter Settings

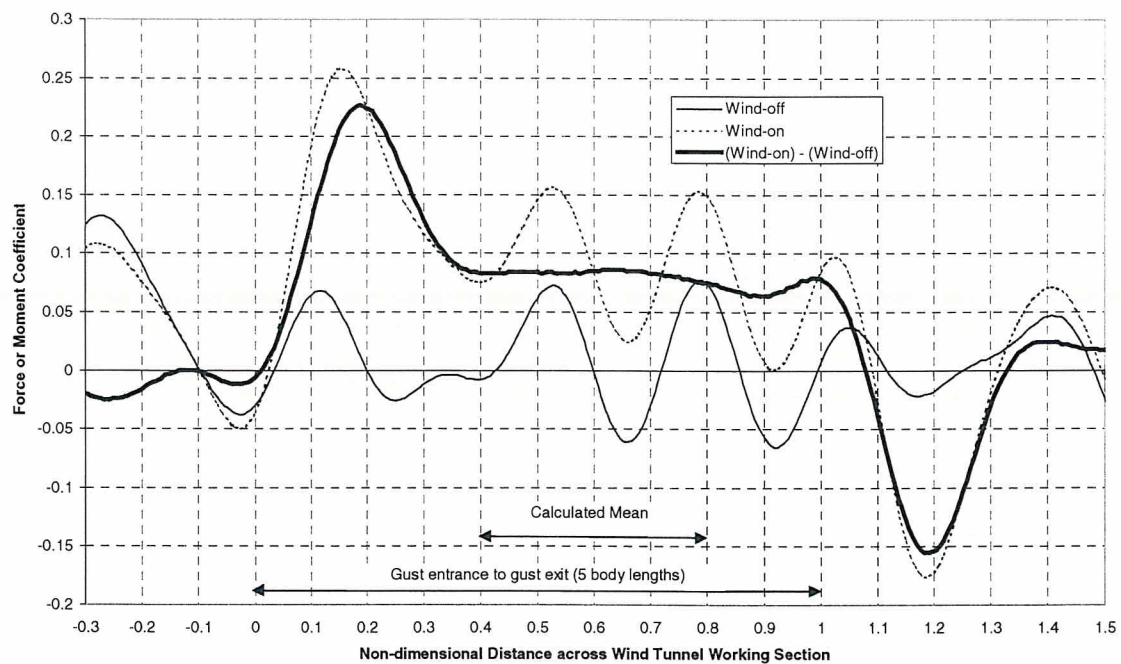


Figure 4-18 Removal of Track Signature at Zero Degree Yaw Angle

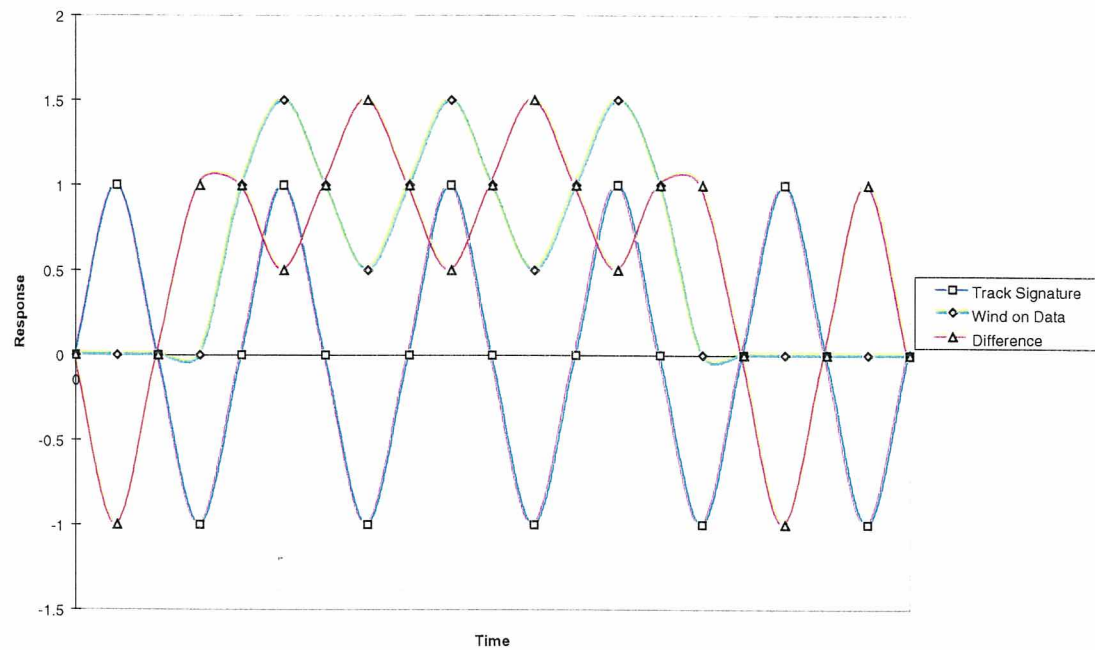


Figure 4-19 Schematic of Error in Superpositioning of Track Signatures

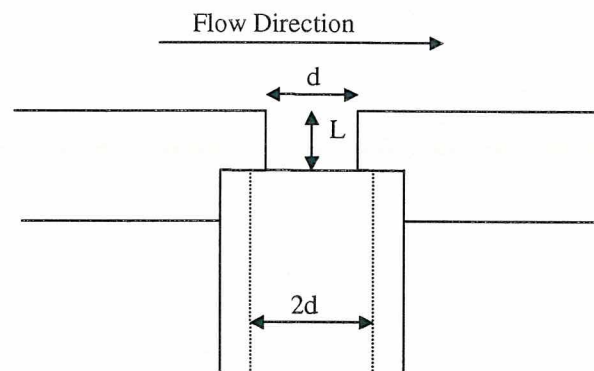


Figure 4-20 Recommended Wall Tapping Geometry. After Benedict⁵⁴

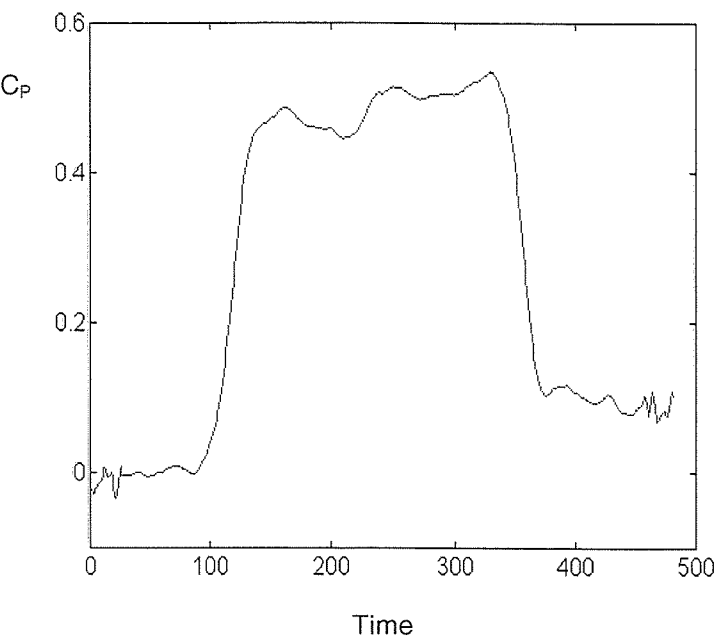


Figure 4-21 Drift Associated with Sealing Pressure Reference at Atmospheric

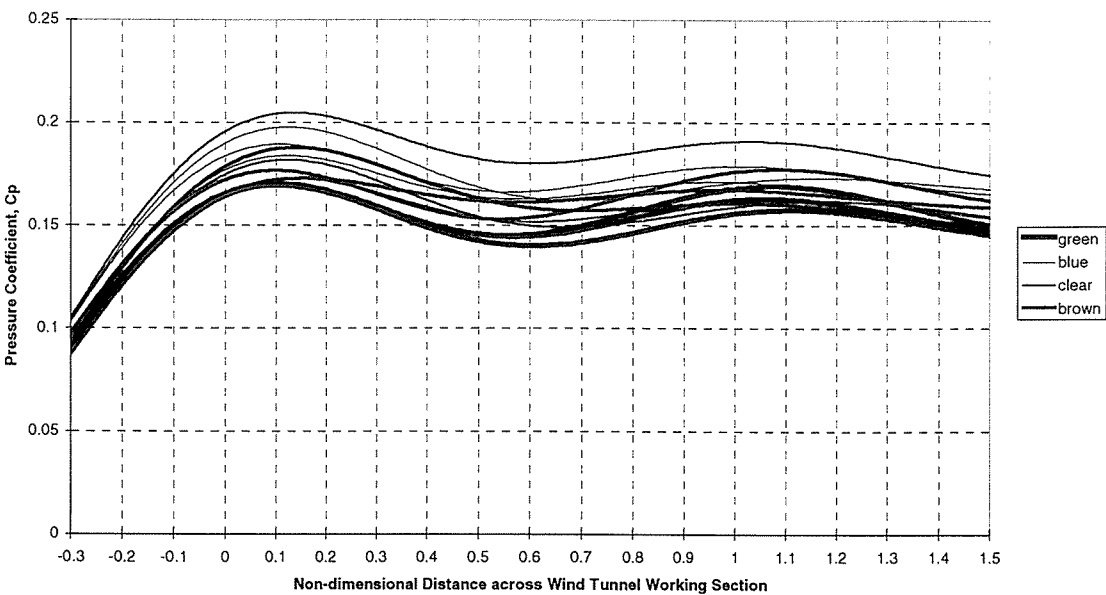


Figure 4-22 Influences of Tapping and Tube Geometry on Pressure Transducer Response

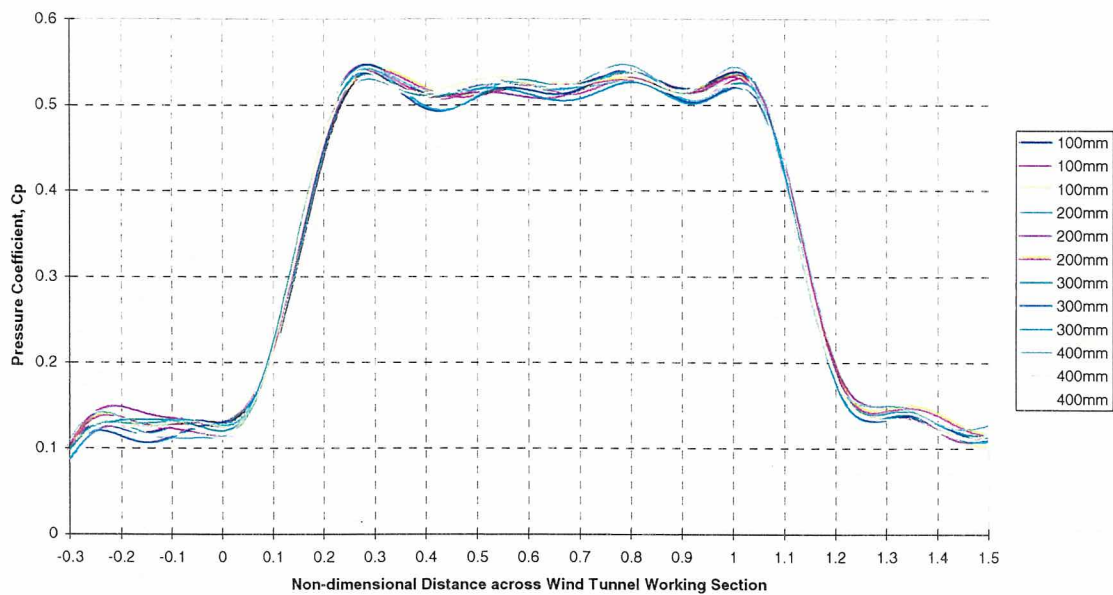


Figure 4-23 Influence of Tubing Length on Pressure Transducer Response

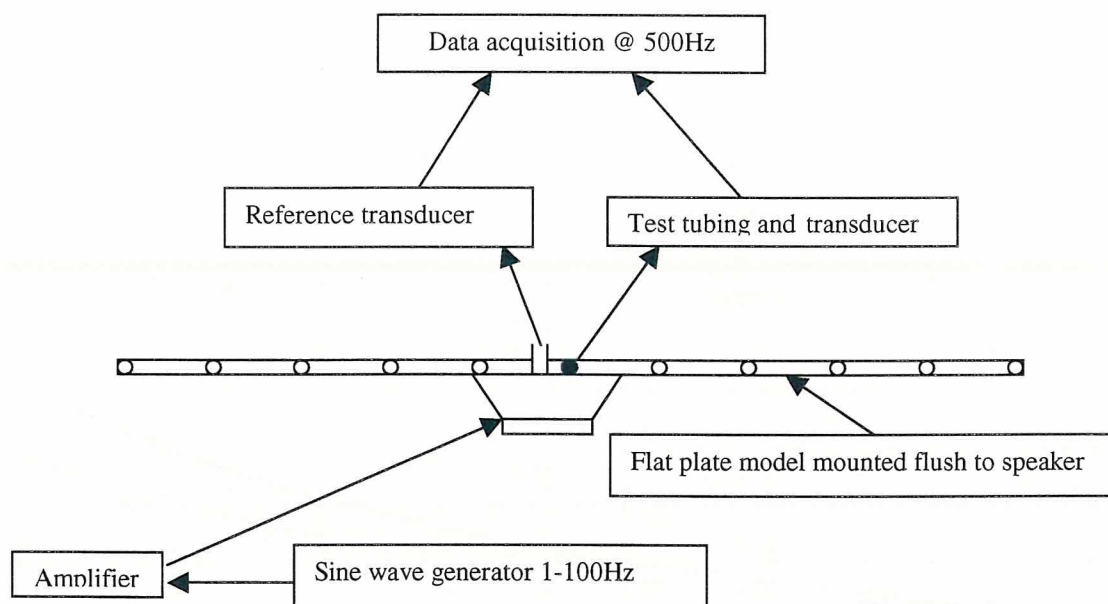


Figure 4-24 Experimental Arrangements for Pressure Transducer Frequency Response Test

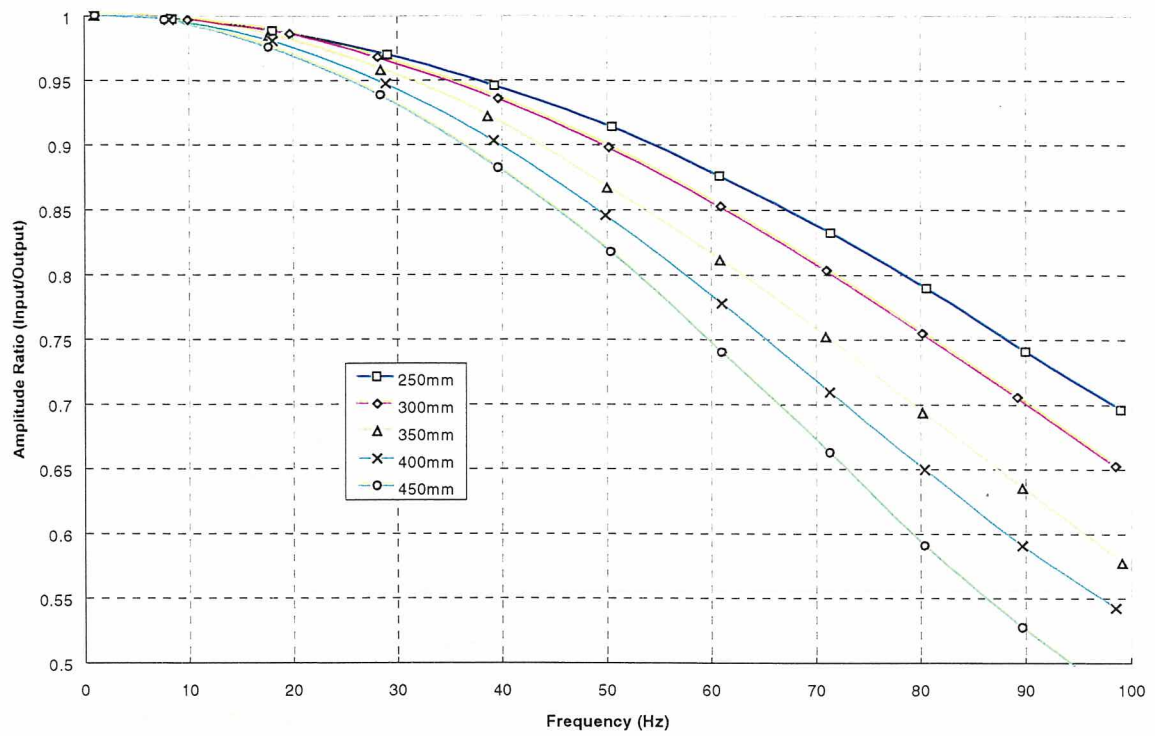


Figure 4-25 Amplitude Ratios for Different Lengths (250 – 450mm) of Connecting Tubing

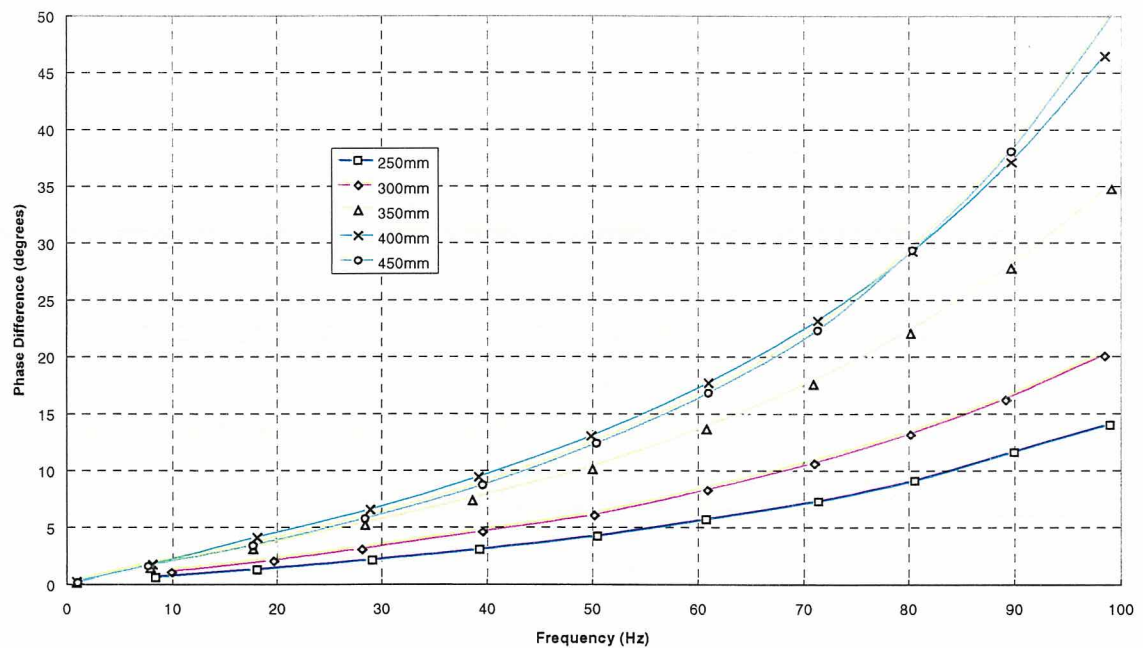


Figure 4-26 Phase Differences for Different Lengths (250 – 450mm) of Connecting Tubing

5. Crosswind Aerodynamics of a Flat Plate Model

5.1 Introduction

In this chapter, force, moment and pressure data for a 480 x 200mm flat plate is presented for the steady state and dynamic test cases. This series of tests served two purposes; firstly, the tests provide a means of validating the test equipment by comparing test data against previously published data. Secondly, the understanding of the fluid flow past a flat plate is a first step towards the understanding of the complex separated flow around SUV's.

Steady state and transient force data is correlated with pressure mapping for the dynamic and steady state cases. Dynamic pressure mapping is presented as a unique transient animation developed during this research program. The animation shows the development and collapse of leeward vortices and provides a detailed picture of the flow field around a flat plate in transient conditions.

For all dynamic tests detailed in this chapter the track speed was set at approximately 13 m/s and the tunnel speed varied to provide 5° yaw angle increment steps from 0 to 25°. For the steady state tests, the tunnel velocity was constant at approximately 13 m/s. The experimental arrangement was that as described in Chapter 4 and with a ground clearance of 30mm.

5.2 Results

5.2.1 Force and Moment Data

Comparing mean side force and yawing moment coefficients versus change in yaw angle (Figure 5-1 and Figure 5-2), it can be seen that both show an approximate linear relationship with increasing yaw. Side force and yawing moment dynamic traces for 5° increments of approximately 5 to 25° yaw angle are shown in Figure 5-3 and Figure 5-4 respectively. Side force dynamic traces have an initial peak 1.7 body lengths ($x/W = 0.34$) after entering the gust and thereafter rise until the leading edge exits the wind tunnel working section. This implies that a steady state condition is not reached in the time taken to traverse the crosswind gust, a distance of 5 body lengths. Lower values of the mean dynamic force coefficients compared to steady state also corroborate this result. This is in agreement with the transient response of passenger vehicles by Docton⁶¹ who found at least 7 body lengths were needed to attain the steady state condition, but in contrast with Kobayashi¹⁴ who suggests 4 body lengths, although an examination of yawing moment traces presented by the latter reveals that this value could be much greater.

There is no obvious increased transient response in the yawing moment dynamic traces on entering or exiting the wind tunnel working section. Various

61. Docton M K R, The Simulation of Transient Crosswinds on Passenger Vehicles, PhD Thesis, Durham University, 1997

filter settings showed that the peaks on entrance and exit are a result of the selected filter. Mean dynamic data (Figure 5-1 and Figure 5-2) is approximately 10-20% lower than steady state data for both side force and yawing moment coefficients, the difference increasing with increasing yaw angle.

5.2.2 Pressure Data

5.2.2.1 Steady State

Figure 5-7 and Figure 5-8 show 3 repeated values of the mean dynamic test windward and leeward pressure distributions along the plate at centre line height for yaw angles 0 to 25°. The figures demonstrate the excellent pressure coefficient repeatability obtainable from the test equipment. Figure 5-9 and Figure 5-10 show average dynamic and steady state centre line surface static pressure distributions for the windward and leeward faces respectively. There is excellent agreement between the steady state and mean dynamic pressure distributions, which is contrary to the recorded force and moment data. If the assumption that a steady state is not reached in the dynamic tests, as indicated by the force data, then differences in flow structure are towards the edges of the plate and not along the centre line. For all yaw angles greater than zero, the recorded pressures increase almost linearly up to 25° yaw for both steady state and dynamic tests. Leeward surface static pressure distributions are dominated by a large negative pressure at the leading edge with peak pressures occurring at 0.9 x/l throughout the range of yaw angles tested. This region of negative pressure extends to approximately 0.6 x/l and thereafter the pressure distributions maintain an approximately uniform profile before approaching an equal value pressure coefficient of approximately 0.25 at the trailing edge of the plate. The windward face pressure distributions show a steady increase with yaw and all approach a pressure coefficient value of approximately 0.2 at the trailing edge of the plate.

Figure 5-11 and Figure 5-12 show mean surface static pressure contour maps of the windward and leeward faces from 0 to 25° for the steady state tests. The figures show the development of the region of strong negative pressure on the leeward side and conversely reduction on the windward face with increasing yaw angle. In addition, the development of areas of negative pressures at the top and bottom edges on the leeward face of the plate is apparent at higher yaw angles. Negative pressures at the top edge of the plate are greater than at the bottom edge due to the effect of ground proximity. The anomalies in data at approximately $x/l=0.2$ and $x/l=0.7$ are due to interference from the model supports.

5.2.2.2 Transient Pressure Animations

Comparisons with the mean surface static pressure contour maps for the dynamic tests (Figure 5-13 and Figure 5-14) show very good agreement with steady state data. This is contrary to the previously recorded force data and supports the assumption that steady state conditions are achieved within the time taken to traverse the crosswind gust. Alternatively, the discrepancy between mean dynamic and steady state forces can also be explained by the

track noise contaminating the balance signal whereas pressure measurements are unaffected by track noise.

Examination of the transient pressure animations for 10° and 20° ('pllee10.mpeg', 'plwind10.mpeg', 'pllee20.mpeg' and 'plwind20.mpeg') show that it is the leeward face that is dominant in the unsteady transient response. The windward face animations show a gradual development of the leading edge positive pressure region on entering and a similar gradual dissipation on exit. Both processes start at the leading edge. However, the leeward face animations are much more complex. The negative pressure region takes longer to reach a steady state after entering the gust and continuously pulses thereafter. After exiting there is a notable change when negative pressure completely collapses at approximately $0.6 x/l$ distance from the trailing edge (most noticeable at 20° yaw angle). Only after all negative pressure has been dissipated does the region of strong negative pressure return at the leading edge.

Figure 5-15 and Figure 5-16 show changes in moment and force coefficients calculated by integration of pressures across each face of the plate during dynamic tests. It can be seen from the figures that the leeward face magnitudes are approximately double those of the windward face. The calculated windward face yawing moment coefficient shows peaks on entering and exiting the gust where there are no increased transient characteristics of the leeward face yawing moment. The integrated forces and moments calculated from pressure measurements are also plotted as dynamic traces in Figure 5-5 and Figure 5-6. Pressure data is filtered at 50Hz whereas force data (Figure 5-3 and Figure 5-4) is filtered at 30Hz and a comparison of the figures shows how the filter changes the dynamic trace (see section 4.5.2). This is evident as incorrect increasing of forces before entering the gust and rounding of the response at the gust entrance and exit. The mean of the integrated pressure forces are also plotted in Figure 5-1 and Figure 5-2 and show reasonable correlation with the measured dynamic side forces but less so compared with the dynamic yawing moments. The accuracy of forces by this method is largely dependent on the grid size. If large pressure changes occur towards the edges of the model, as is anticipated here, then some inaccuracy will inevitably occur.

The locations and magnitudes of peak pressures on the leeward face are included in Figure 5-17 and Figure 5-18. For all yaw angles the position of peak pressure fluctuates around a point $0.9 x/l$ from the trailing edge. Above 15° this trend changes rapidly after exiting the gust where the position of peak pressure is approximately $0.6 x/l$ from the trailing edge. This data correlates well with the collapse of the leeward separation bubble identified in the transient pressure animations. As would be expected, the magnitudes of peak pressures vary to a great degree. There is evidence of a maximum peak negative pressure on entering the gust at 25° yaw angle but this is not consistent for all yaw angles. A minimum peak negative pressure occurs just after exiting the gust for all yaw angles which is coincident with the position of peak pressure at $0.6 x/l$ from the trailing edge.

5.2.3 Flow Visualisation

Previous flow visualisation for the steady state tests by Garry⁵¹ showed that there is a strong vortex emanating from the upper leading edge of the plate. It was found that this vortex does not obviously break down between 5° and 55° in steady state tests, however a sudden change in recorded yawing moment against yaw suggested some form of flow separation occurred above 35° . Figure 5-19 shows flow visualisation using the College of Aeronautics 100mm smoke tunnel at 10° , 20° , 30° , and 40° . The flow pattern in the wake is dominated by a large helical vortex originating from the upper leading edge of the plate and which grows as the yaw angle increases. A similar vortex also originates from the lower leading edge but this is not as strong and is harder to trace at higher yaw angles. The vortex separates at approximately 40° which is coincident with the peak in side force coefficient identified by Garry.

Stills taken from the flow visualisation video of the leeward face of the plate for 0° – 25° yaw using fluorescent microtufts are shown in

Figure 5-20. At 0° yaw there is a small region of reversed flow at the leading edge of the plate that grows with increasing yaw. Reversed flow is evident at the centre region towards the leading edge and the main direction of flow is from the upper and lower leading edge corners towards the centre of the plate as indicated in the schematic in Figure 5-21. Flow is then forced out either side of the main thrust of flow and joins the central turbulent reversed flow region or is directed towards the upper or lower edges of the plate. Accelerating flow at the upper and leading edges is then helped by the forced out flow and large helical vortices are generated as previously shown in Figure 5-19.

5.3 Discussion

5.3.1 Previous Work

Considering that the flat plate is one of the most fundamental and simplest shapes for an aerodynamicist to investigate, there is surprisingly little previously published research on the subject and apart from the work of Garry⁵¹, little of direct relevance to the current research. Garry collected force and moment data of an identical plate using the same test equipment. Steady state data shows an excellent comparison of both side force and yawing moment coefficients even though data was collected at much higher Reynolds numbers. The data identified stalling of the plate at approximately 40° yaw and tests on other plates revealed that the stall occurs at higher yaw angles with increasing aspect ratio. Unfortunately, dynamic data was only collected at yaw angles above 25° and comparison is not possible, though the trends of side force and yawing moment dynamic traces are very similar to that previously described.

Investigations by Fage⁶² concentrated on determining the structure of the vortex system in the wake of a flat plate of infinite span and as such, much of the data

62. Fage A and Johansen F, On the Flow of air behind an Inclined Flat Plate of Infinite Span, Proc. Royal Soc., series A, vol. 116, pp. 170-197, 1927

is available for higher angles of yaw and not for attached flow as is the case here. Of the 2 yaw angles available for comparison (6^0 and 15^0), pressure mapping of the windward face showed good agreement with the current research despite the differences in test technique, notably ground proximity and a 3 dimensional flow field. For the leeward face, Fage⁶² measured a uniform base pressure across the width of the plate for the 15^0 yaw case, inferring that flow had completely separated from the plate surface at and above this yaw angle. An examination of the leeward centre line pressure distributions of Figure 5-10 show that there is never a uniform base pressure for all yaw angles tested in this research. The plate used by Fage⁶² was approximately a quarter the width of the plate used here and it is appreciated that detachment of flow occurred at appreciably lower values of yaw than the current research. The theories developed by Fage⁶² are then dependent on plate aspect ratio, a problem later addressed by Abernathy⁶³. Fage⁶² also estimated the normal force based on integration of pressure measurements around the centre line of the plate but these values do not correlate well with the current research presumably because of the difference of 2 and 3 dimensional flow fields.

Abernathy⁶³ used the results of Fage⁶² to modify the free-streamline theory previously developed by Roshko⁶⁴. Data was collapsed in such a way so that a modified Strouhal number could be determined independent of angle of attack and lateral constriction (Abernathy⁶³ defined lateral constriction as the ratio of plate chord to wind tunnel height). However, the theory only holds for unattached surface flows at high angles of yaw and none of the data can be used for comparison with the results presented here.

Of more use is the analytical model proposed by Yeung⁶⁵ which combines the modified free-streamline theory mentioned previously with the partially developed wake flow model of Wu⁶⁶. The model accurately predicts centre line pressure distributions at higher angles of attack but again fails with yaw angles less than 15^0 . An attempt to model yaw angles lower than 15^0 was made by introducing incomplete separation at the leading edge, and hence development of a separation bubble, and gives favourable agreement with the experimental data of Fage⁶² at 6^0 . When comparing to the present research, there is reasonable correlation for the leeward and windward face but again results are dependent on aspect ratio of the plate and the leeward face flow field is on the verge of separation even as low as 6^0 .

5.3.2 Flow Characteristics around an Inclined Flat Plate

Considering the combined force, pressure and flow visualisation studies, a clear picture of the flow field around the flat plate emerges. For the steady state condition, separation occurs at the front edge of the plate, the strength of the separation bubble increasing on the leeward face and conversely decreasing on

63. Abernathy F, Flow Over an Inclined Plate, Trans. AMSE, J. Basic Eng., vol. 84, pp. 380-388, Sept. 1962

64. Roshko A, A new hodograph for free-streamline theory, NACA Tech. Note 3168, 1954

65. Yeung W and Parkinson G, On the Steady Separated Flow around an Inclined Flat Plate, J. Fluid Mech., vol. 333, pp. 403-413, 1997

66. Wu T, Cavity and Wake Flows, Ann. Rev. Fluid Mech., vol. 4, pg. 243, 1972

the windward face with increasing yaw angle. The growth of the leeward leading edge separation bubble is coincident with the development of lengthwise vortices along the upper and lower edges of the plate. The lower vortex is weaker than the upper due to the effect of ground proximity.

The magnitudes of pressure on the leeward face are approximately double those on the windward showing that the leeward face contributes the greater proportion of side force and yawing moment characteristics.

The transient response shows on first sight little difference to the steady state. Dynamic traces show no increase in yawing moment on entering the crosswind gust up to the yaw angle range relevant to this research of 25° . This is in itself an interesting result, since it would be expected that at the point when half the body is immersed in the gust there would be an increased yawing moment. This can be explained by the high steady state yawing moment resulting from a concentration of loading at the leading edge, any transient peak being insignificant in comparison.

Examination of the transient pressure animation has shown that the primary transient characteristic of flat plates is a leeward separation bubble collapse on exiting the crosswind gust. The leeward pressure distribution does not return to the zero yaw case in the manner expected and only after all negative pressure has been dissipated does the separation bubble return at the front of the plate.

Of all the results collected in this chapter perhaps the most difficult to interpret are the changes in magnitude and location of peak pressure on exiting the gust as shown in Figure 5-17 and Figure 5-18. The change in flow field at this point could be attributed to flow being forced out of the tunnel walls as the model is exiting the gust (as shown schematically in Figure 5-22). This action could conceivably change the flow direction on the windward face but it is unlikely that this would promote the leeward vortex collapse as seen on the transient pressure animations. Additionally, there is open space above the model and the gap in the wind tunnel working section extends to $\frac{3}{4}$ body length either side of the model. Neither of these boundary conditions would be expected to constrict the flow.

5.4 Conclusions

From this series of tests on a flat plate model the following conclusions can be made. Concerning the test equipment:

1. The steady state condition is not achieved in dynamic tests during the time taken to traverse the gust, a distance of 5 body lengths
2. The dynamic pressure measurement system has been shown to give good pressure coefficient accuracy and repeatability
3. Integration of pressures to give dynamic force and moment changes is a better method of observing transient forces than by conventional balance. This is because pressure measurement does not suffer from signal noise contamination, however the accuracy of integrated forces is limited by pressure grid size.

Concerning the aerodynamic characteristics of a flat plate:

4. The changes in steady state force and pressure measurement show a linear relationship with increased yaw up to the maximum yaw angle tested (25°)
5. The flow field around an inclined flat plate is characterised by development of a leeward separation bubble and longitudinal vortices with increasing yaw
6. There is little difference between the dynamic and steady state response of the flat plate. Transient characteristics at the gust exit can be identified on the pressure animations but cause little change in the force coefficients.

The correlation of force, pressure and flow visualisation measurements has proved very useful in determining the flow pattern around an inclined flat plate. Further chapters will now describe the flow regime around three-dimensional objects to further understand the complex separated flow around bluff bodies and SUV's.

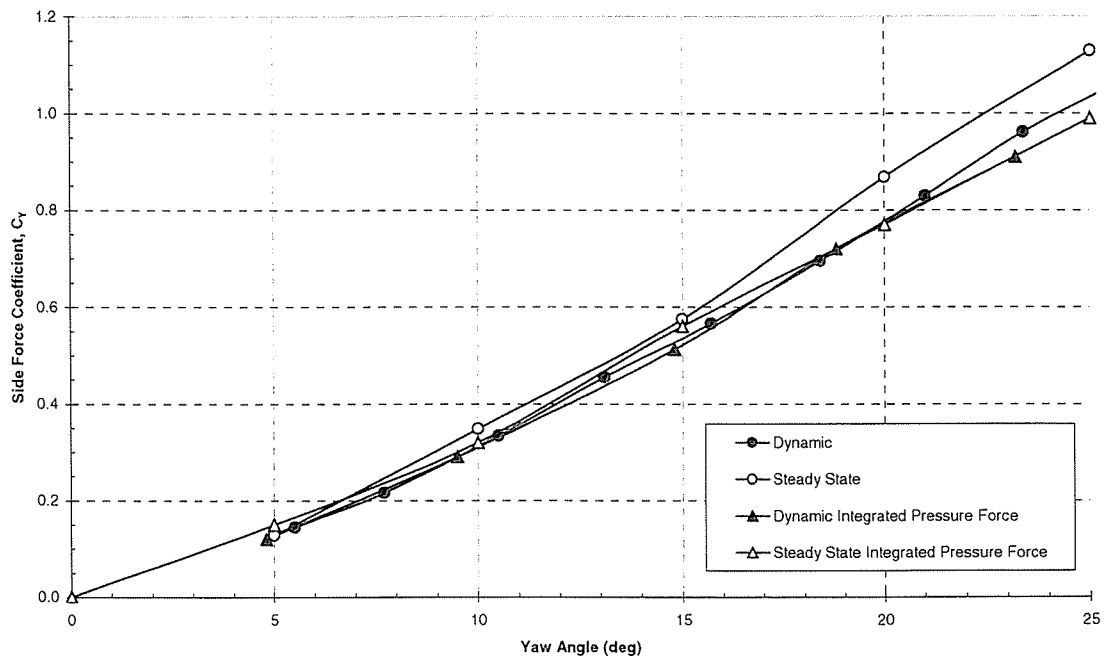


Figure 5-1 Variation of Side Force Coefficient with Yaw Angle for Flat Plate

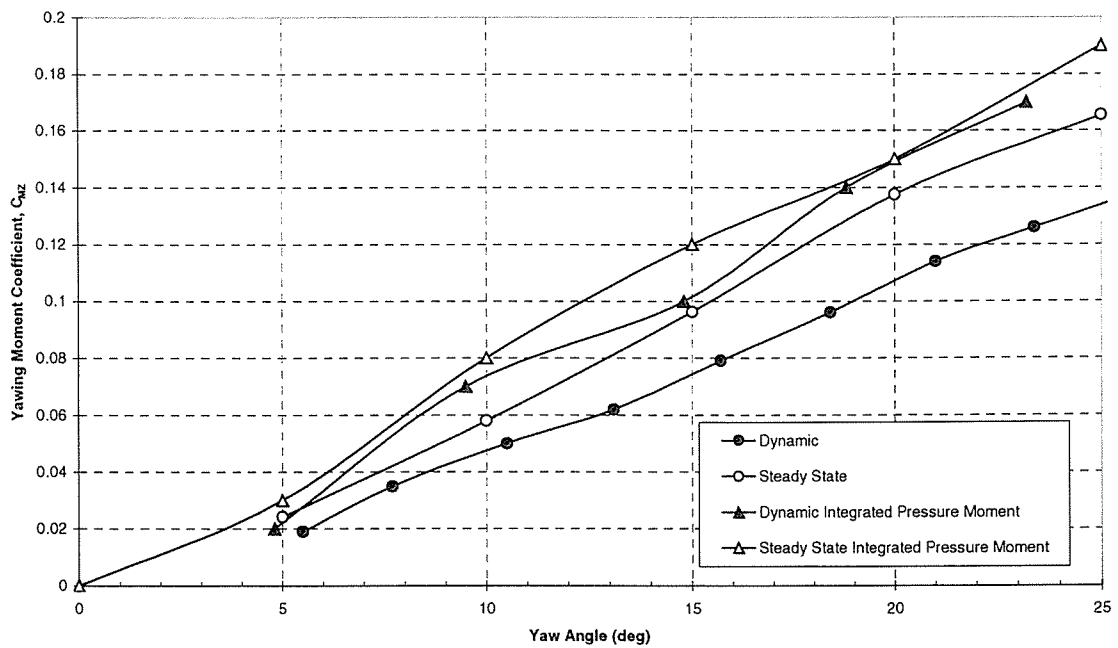


Figure 5-2 Variation of Yawing Moment Coefficient with Yaw Angle for Flat Plate

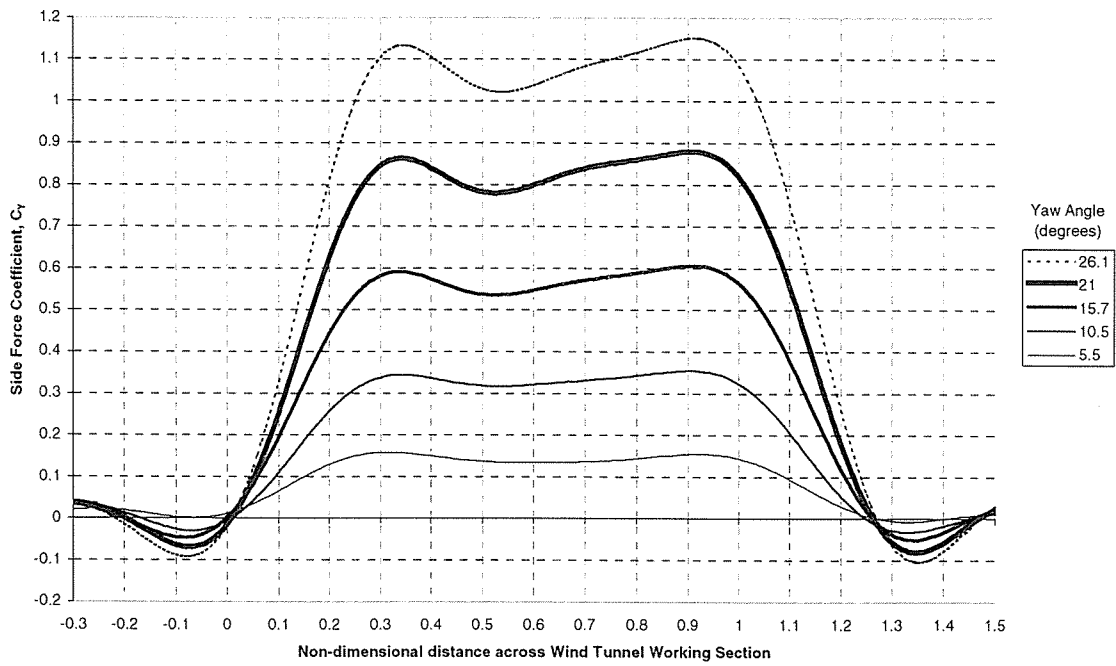


Figure 5-3 Flat Plate Side Force Coefficient Dynamic Traces, 5 to 25° yaw

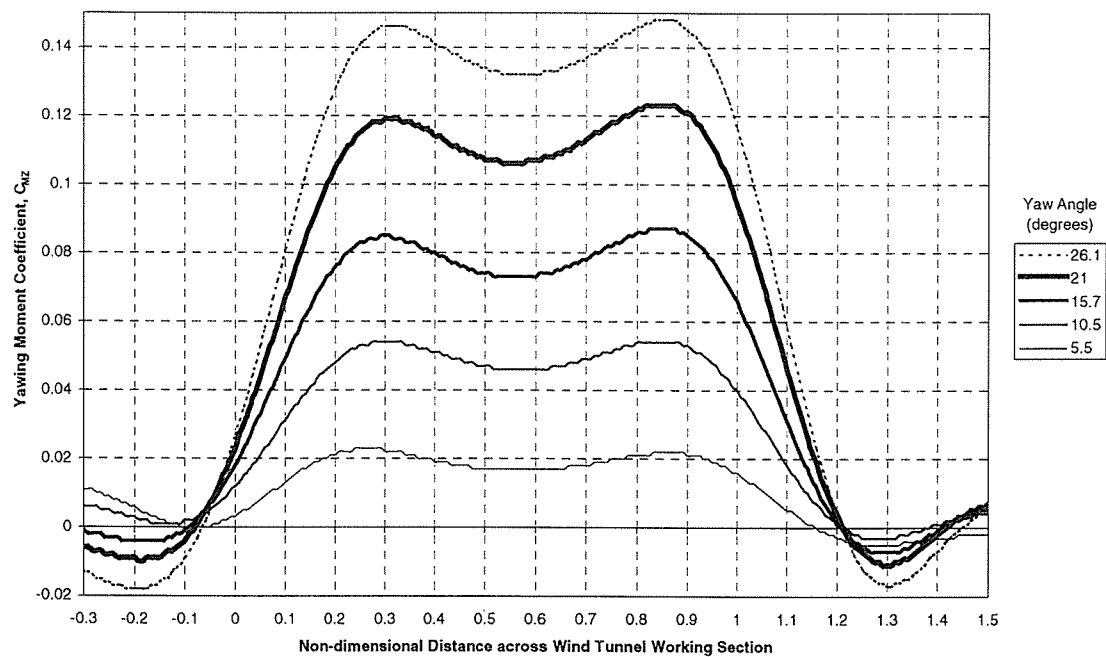


Figure 5-4 Flat Plate Yawing Moment Coefficient Dynamic Traces, 5 to 25° yaw

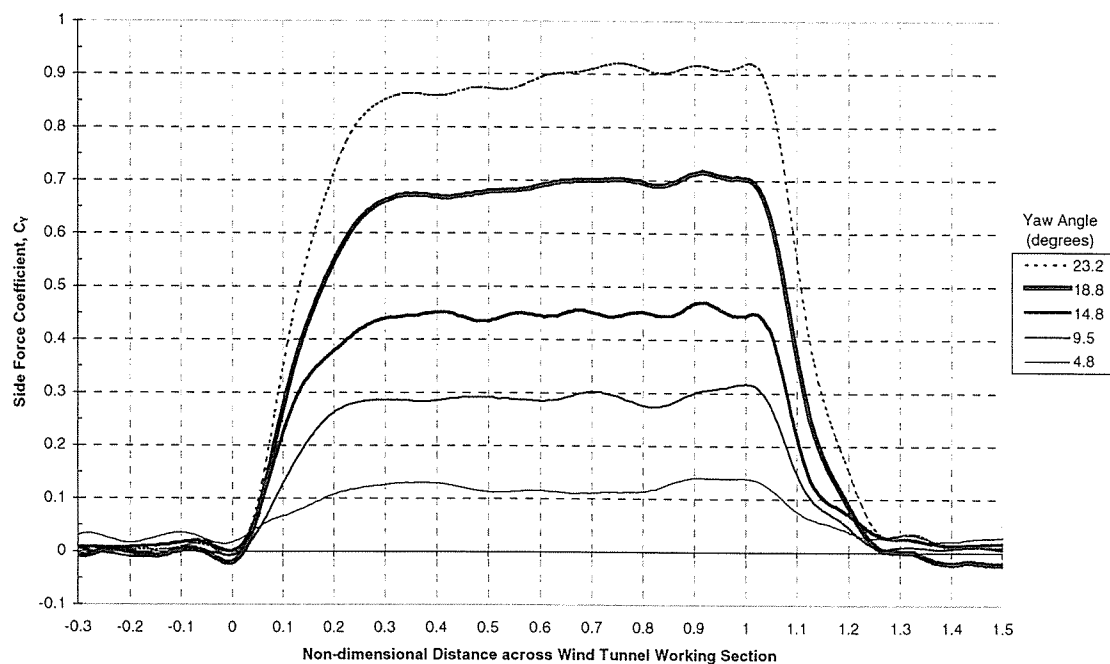


Figure 5-5 Flat Plate Side Force Coefficient Dynamic traces Calculated from Integrated Pressure Distributions

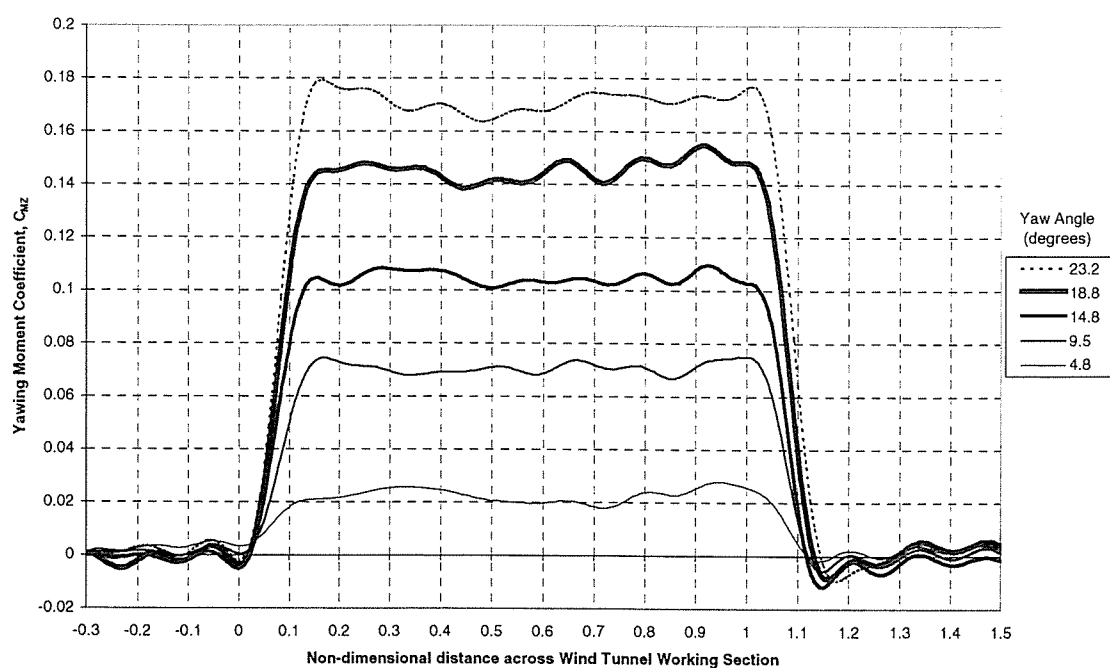


Figure 5-6 Flat Plate Yawing Moment Dynamic traces Calculated from Integrated Pressure Distributions

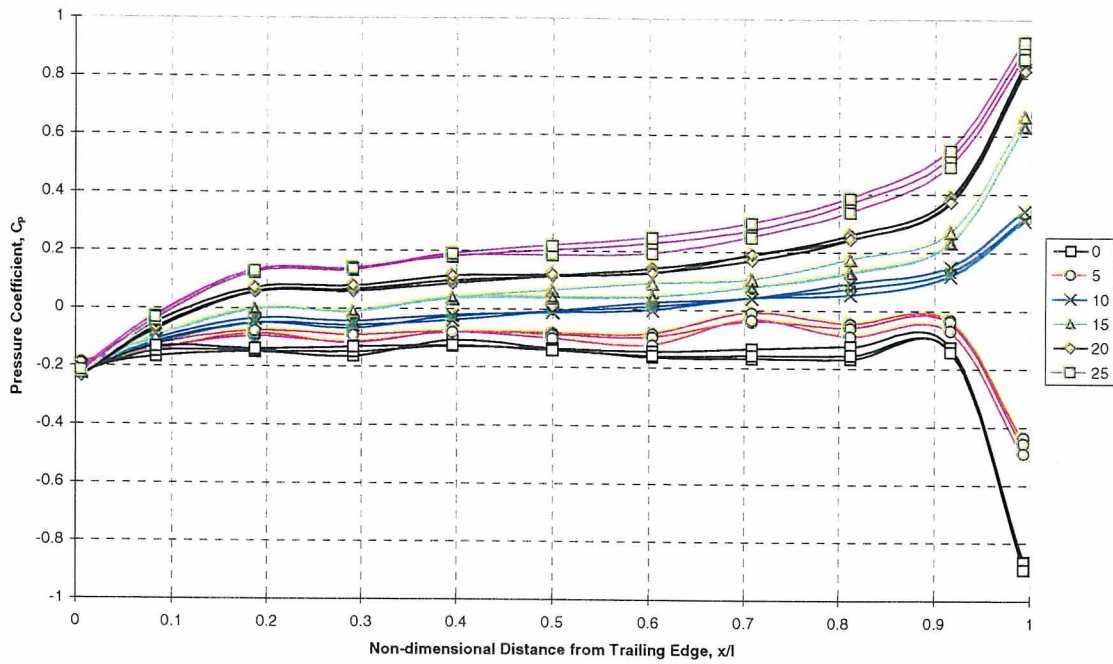


Figure 5-7 Mean Dynamic Windward Centre Line Pressures Yaw Angles 0 to 25°, Leading edge to right of page

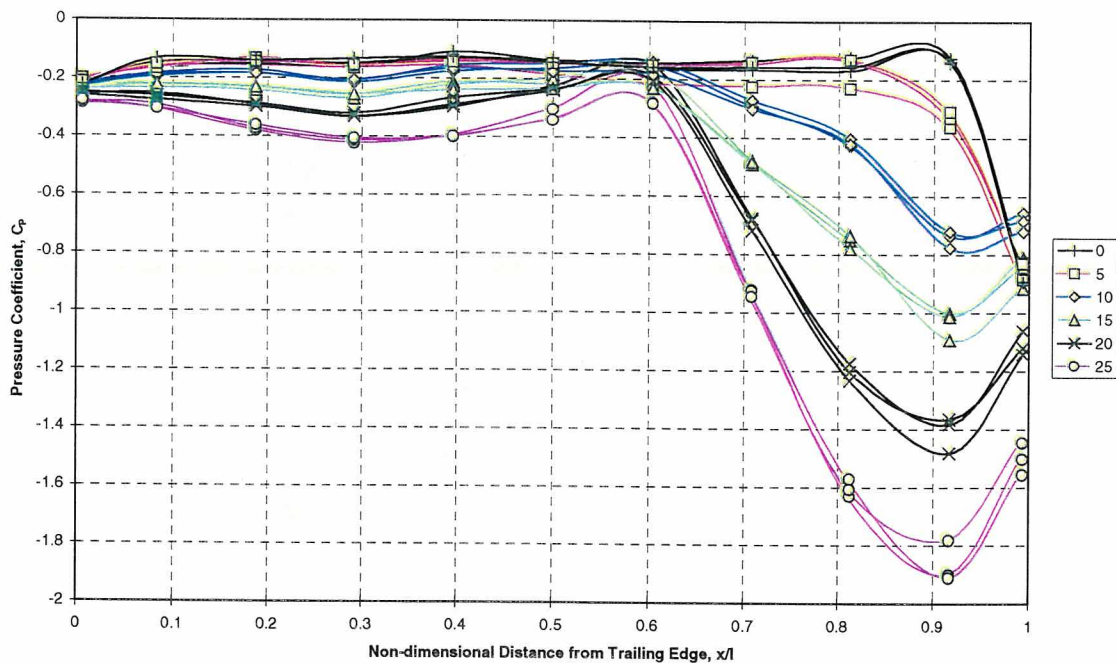


Figure 5-8 Mean Dynamic Leeward Centre Line Pressures Yaw Angles 0 to 25°, Leading edge to right of page

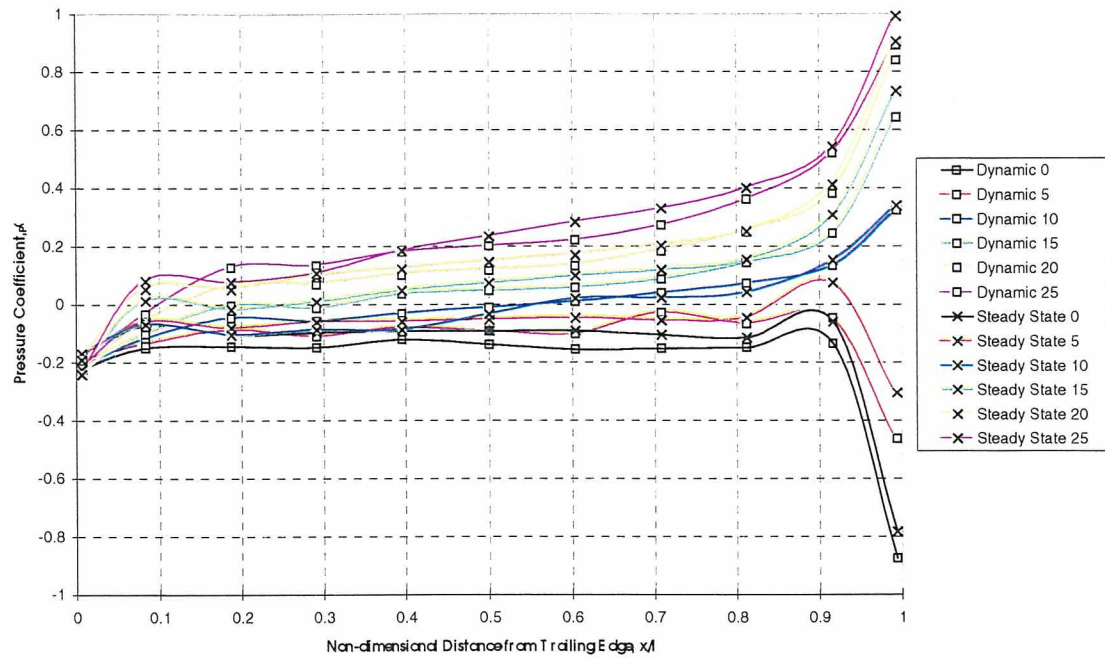


Figure 5-9 Comparison of Mean Dynamic and Steady State Test Windward Centre Line Pressures

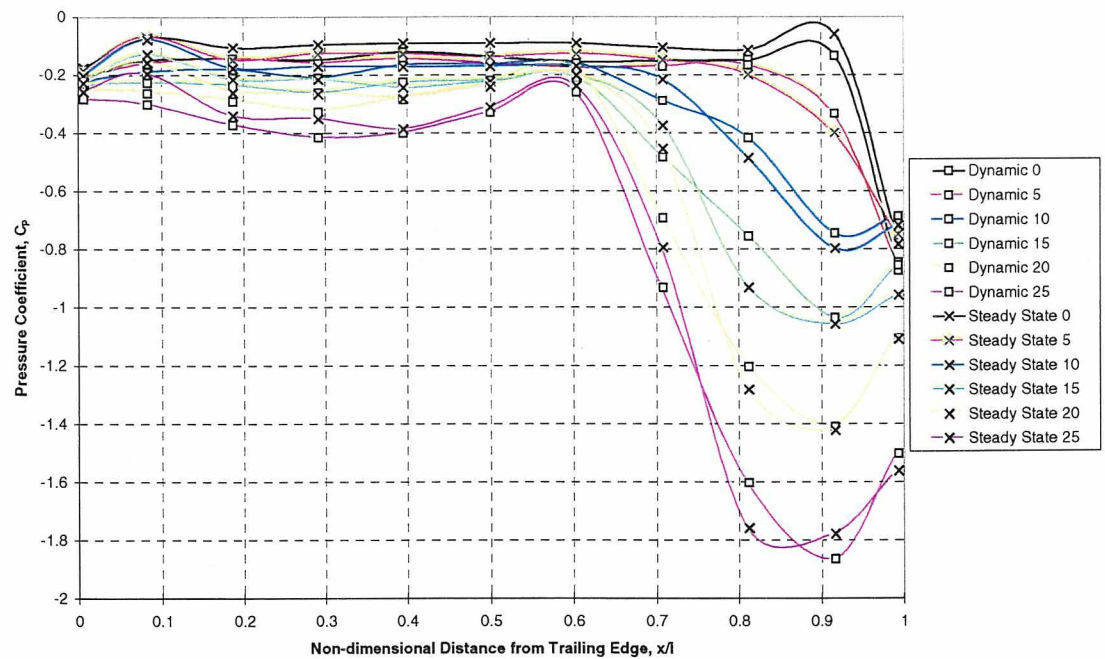


Figure 5-10 Comparison of Mean Dynamic and Steady State Test Leeward Centre Line Pressures

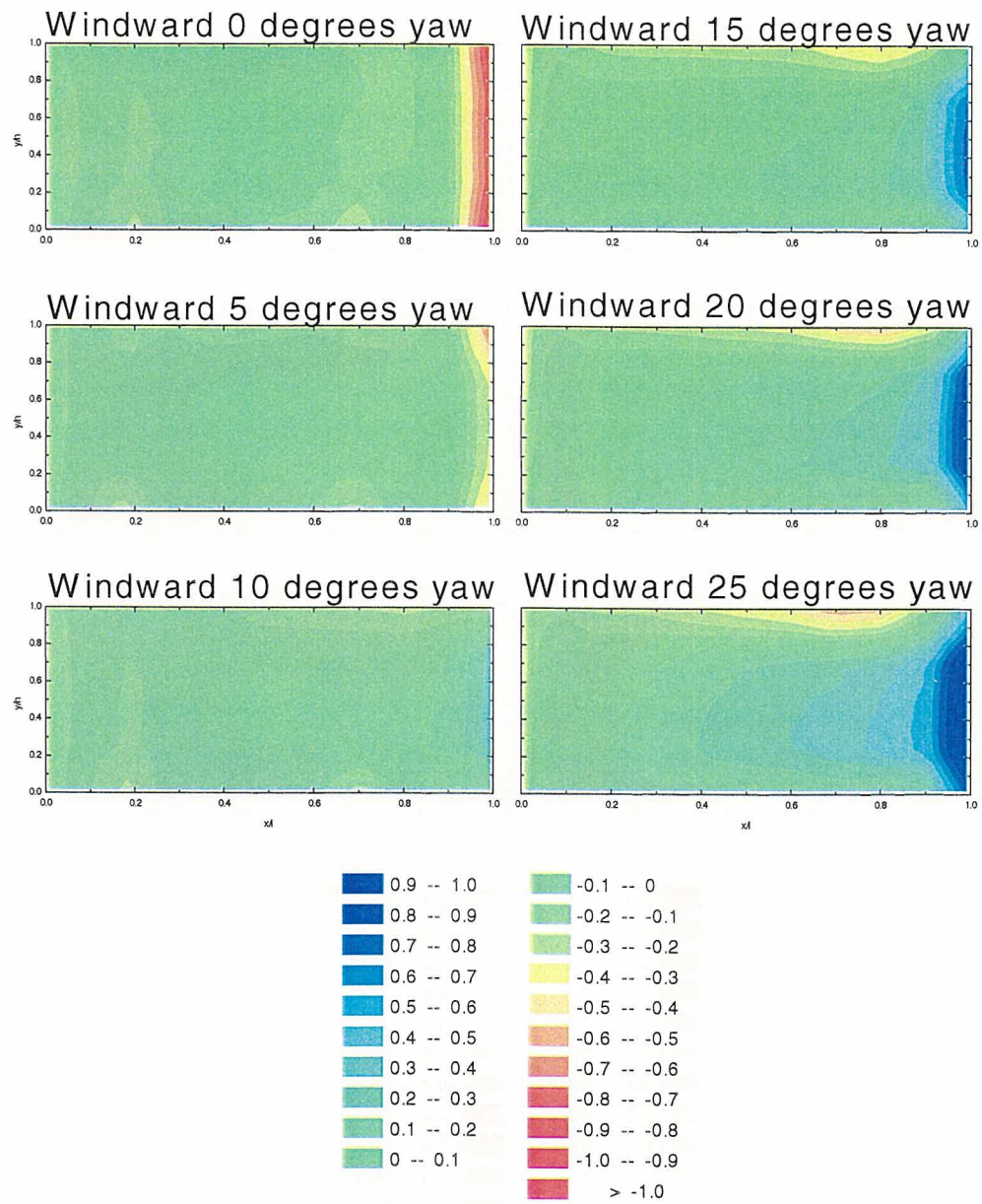


**Figure 5-11 Flat Plate Steady State Pressure Distribution of Windward Face (0-25°)
Leading Edge to Right of Page**

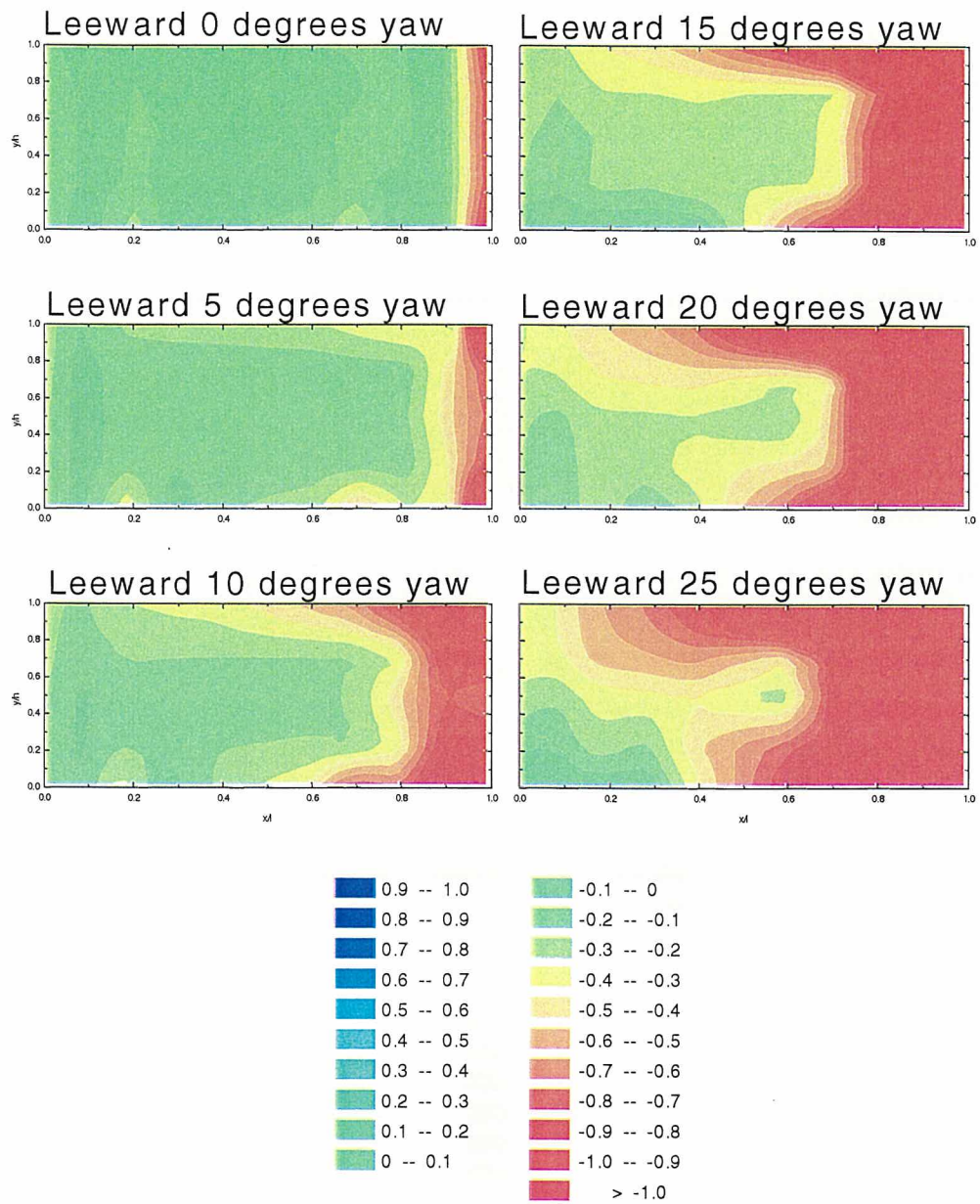


Figure 5-12 Flat Plate Steady State Pressure Distribution of Leeward Face (0-25°) Leading Edge to Right of Page

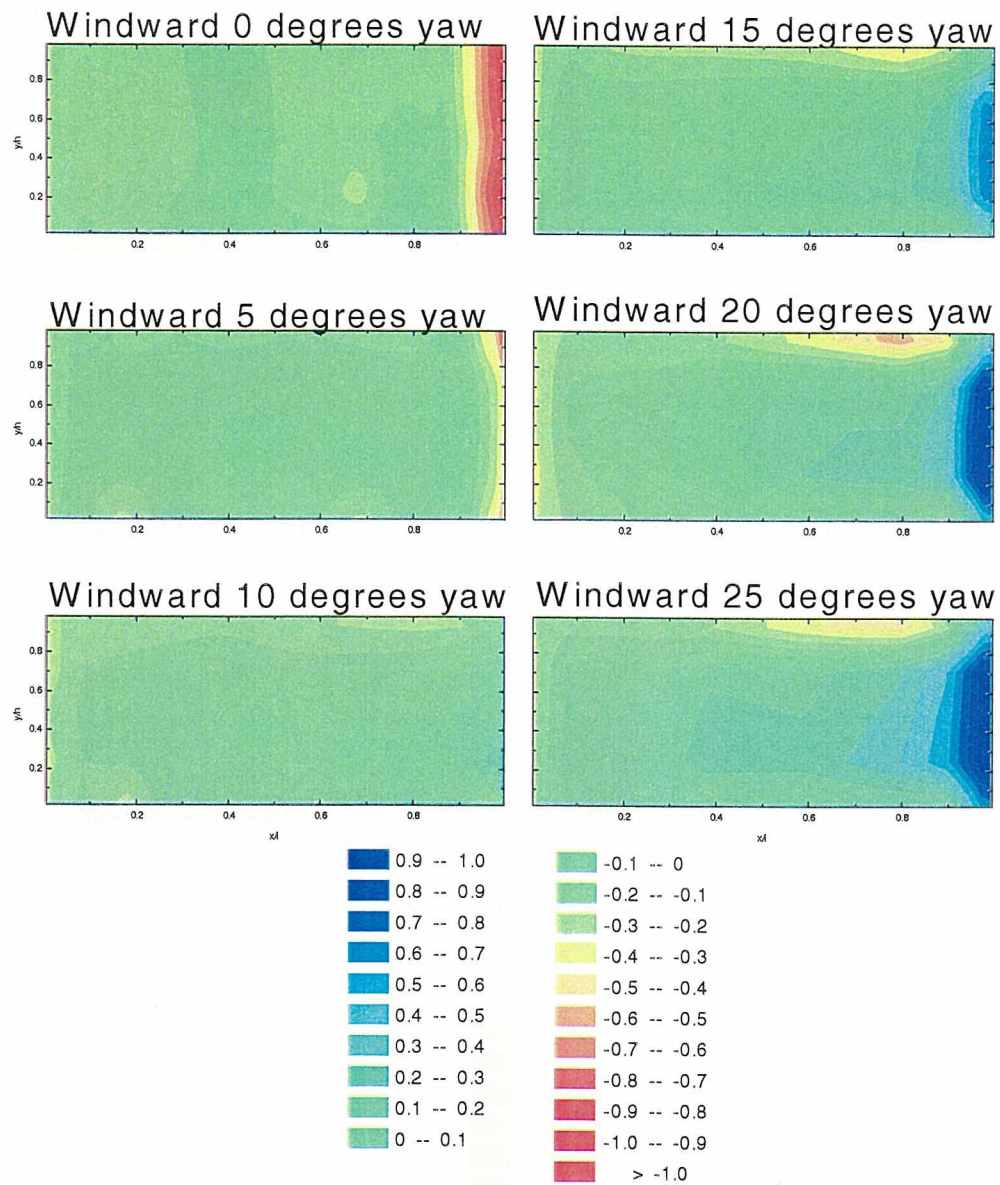


**Figure 5-13 Flat Plate Mean Dynamic Pressure Distribution of Windward Face (0-25°)
Leading Edge to Right of Page**

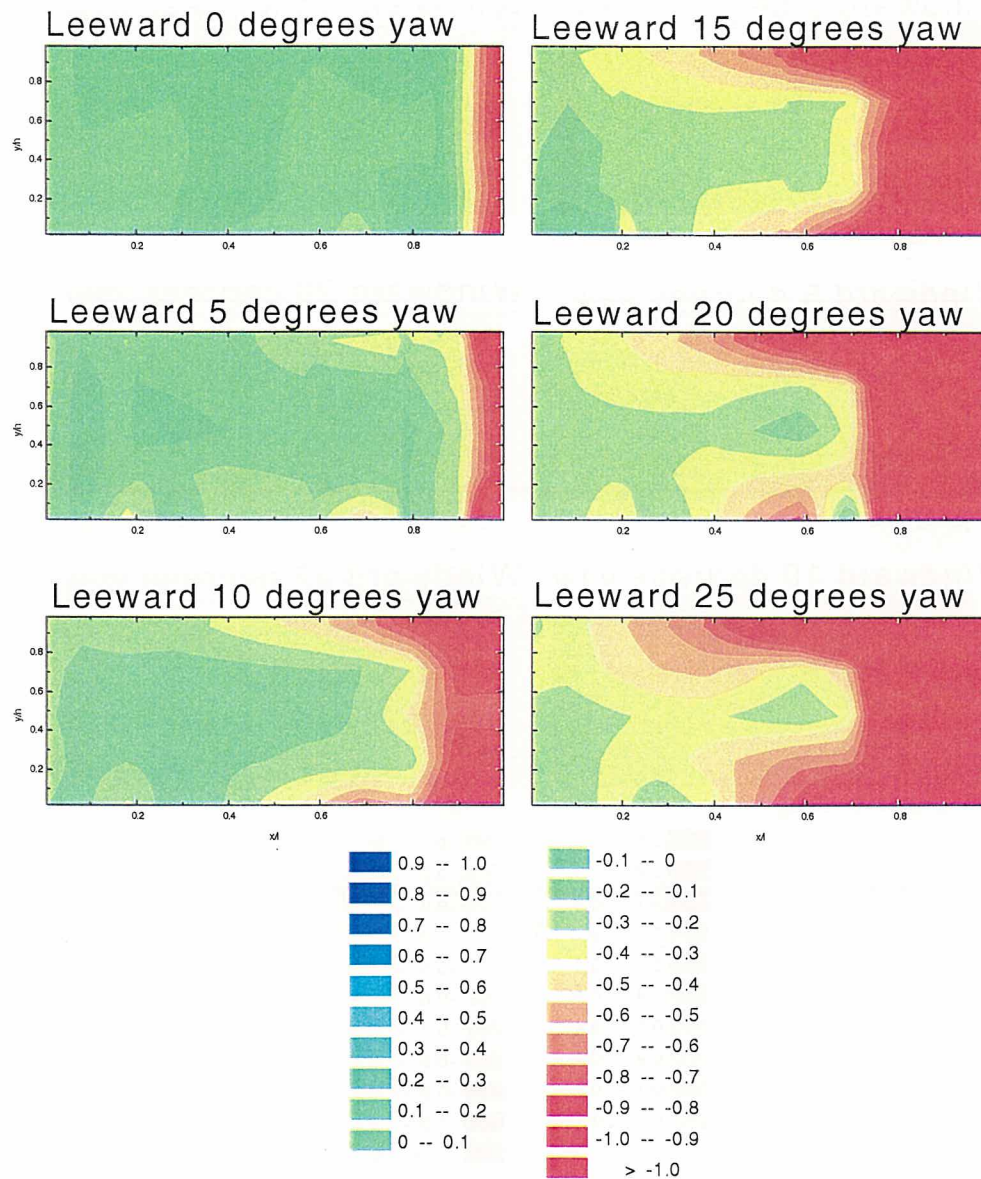


**Figure 5-14 Flat Plate Mean Dynamic Pressure Distribution of Leeward Face (0-25°)
Leading Edge to Right of Page**

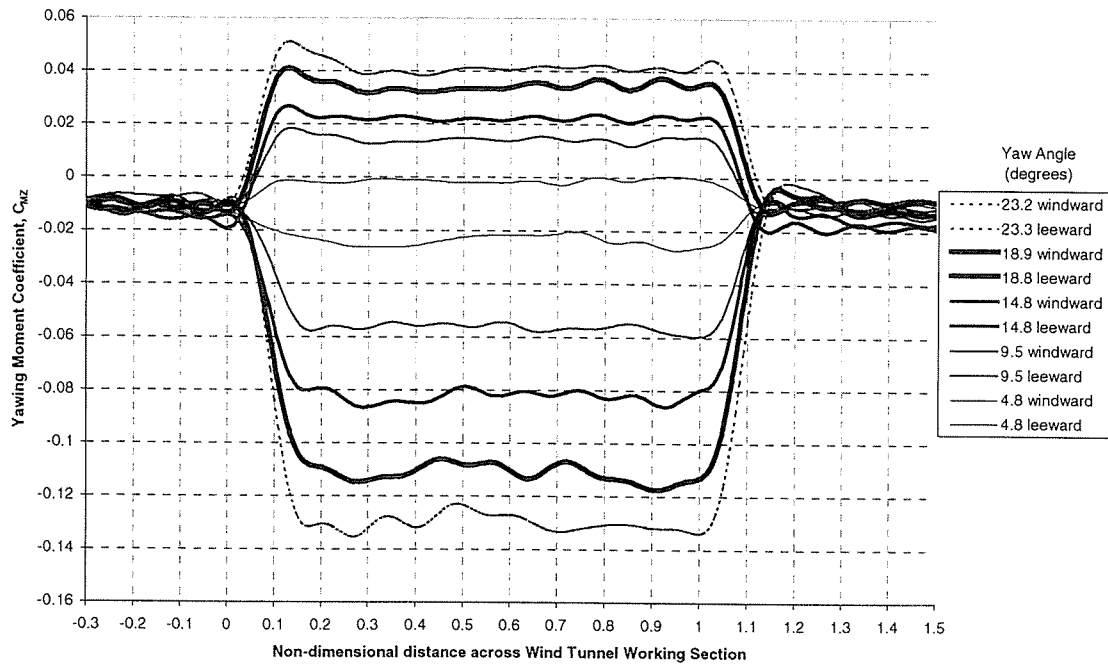


Figure 5-15 Yawing Moment Coefficient Changes on each Face Integrated from Dynamic Pressure Distributions

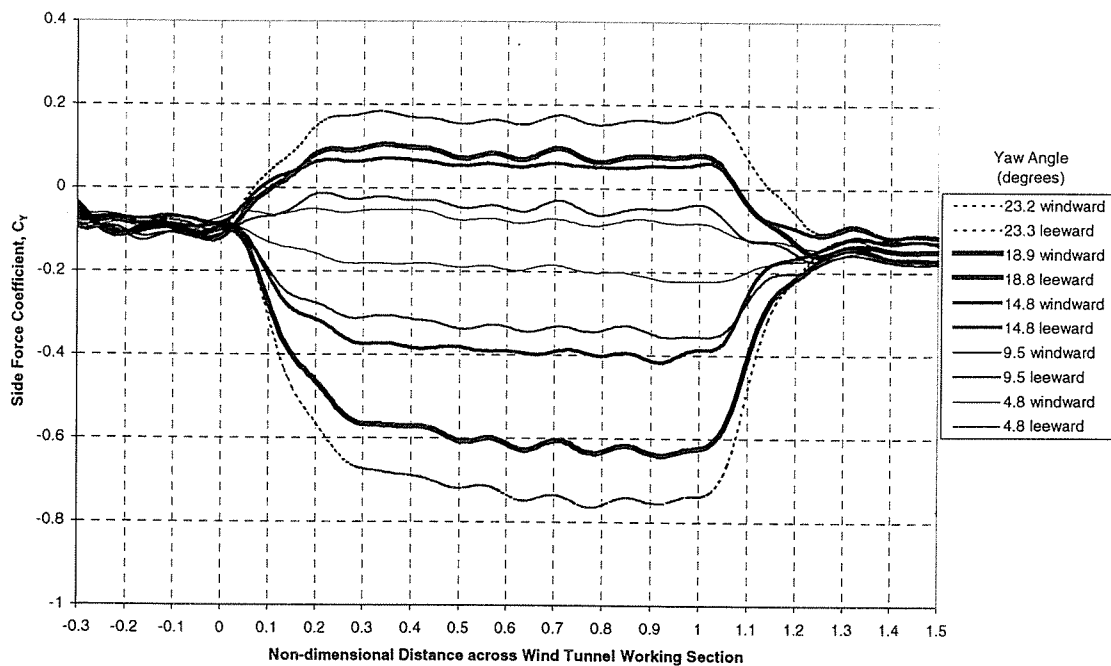


Figure 5-16 Side Force Coefficient Changes on each Face Integrated from Dynamic Pressure Distributions

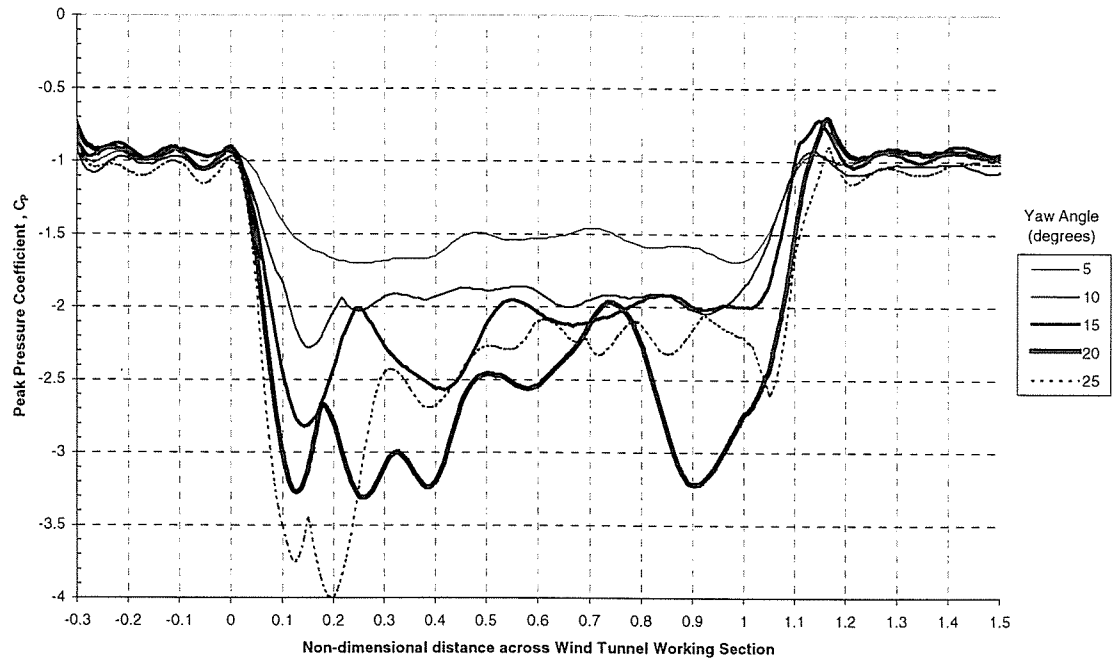


Figure 5-17 Flat Plate Transient Minimum Peak Pressures for 5 - 25° yaw angle

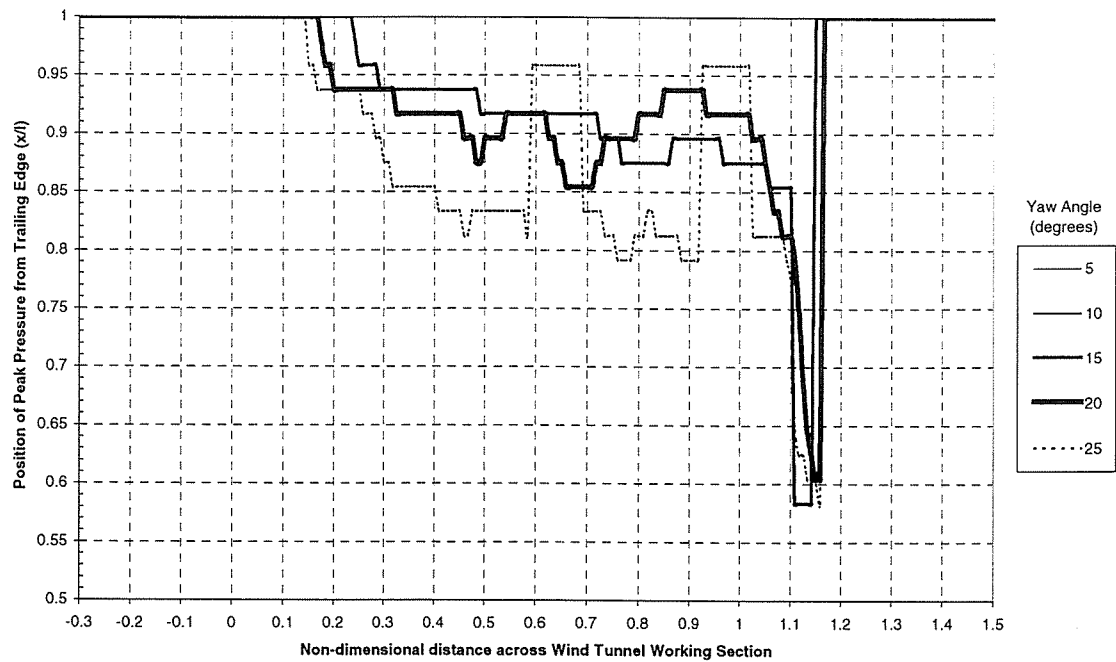
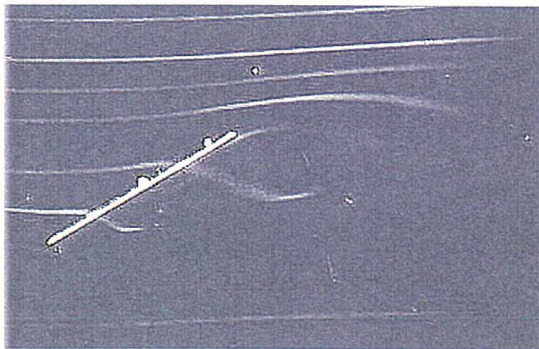


Figure 5-18 Positions of Flat Plate Transient Peak Pressures for 5 - 25° yaw angle

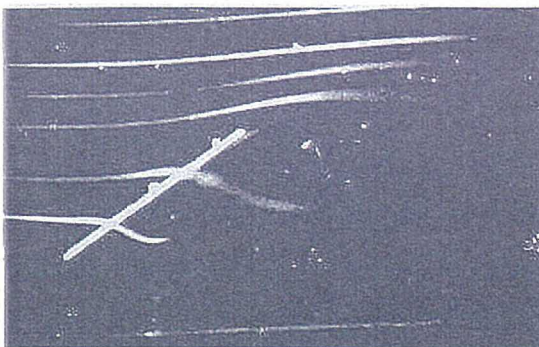
10° Yaw Angle



20° Yaw Angle



30° Yaw Angle



40° Yaw Angle

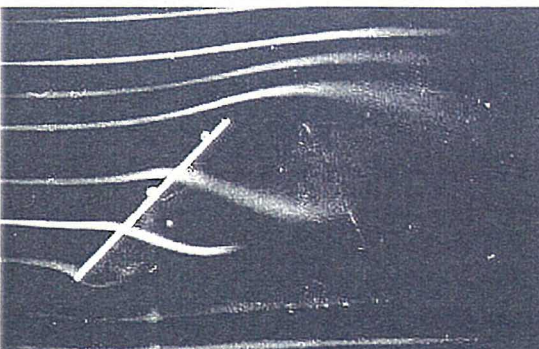
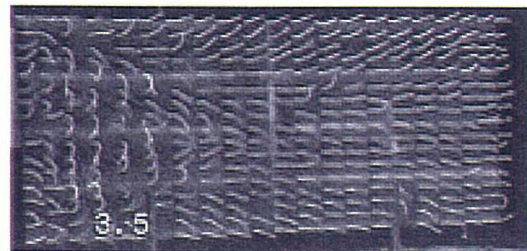


Figure 5-19 Flat Plate Flow Visualisation by Smoke Trace, Yaw Angle 10 - 40°

Leading Edge to Left of Page



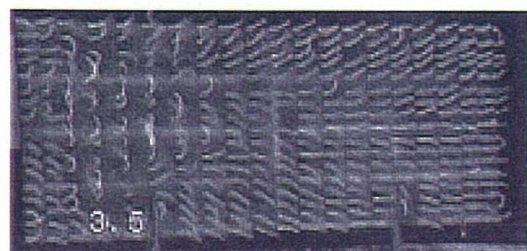
0° Yaw



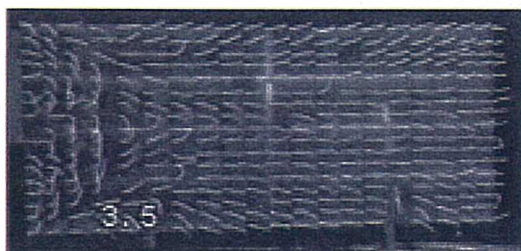
15° Yaw



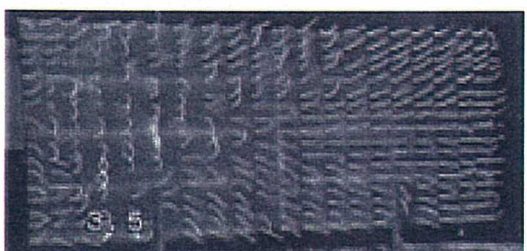
5° Yaw



20° Yaw



10° Yaw



25° Yaw

Figure 5-20 Stills off Film Taken of Flat Plate Leeward Face Flow Visualisation by Fluorescent Tuft, Yaw Angle 0 - 25°

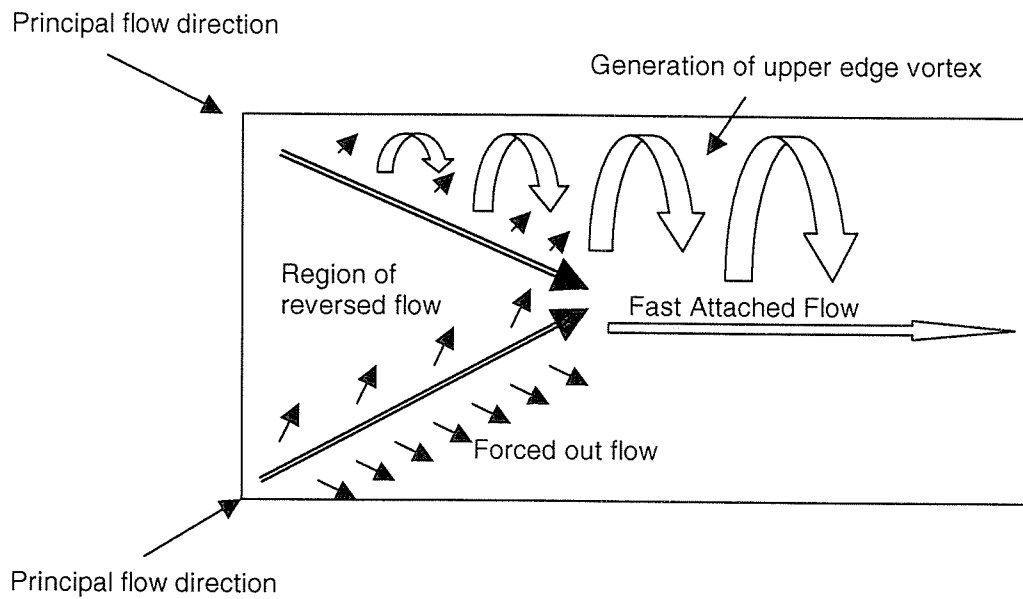


Figure 5-21 Generalised Flow Structure of Flat Plate Leeward Face. Leading Edge to Left of Page

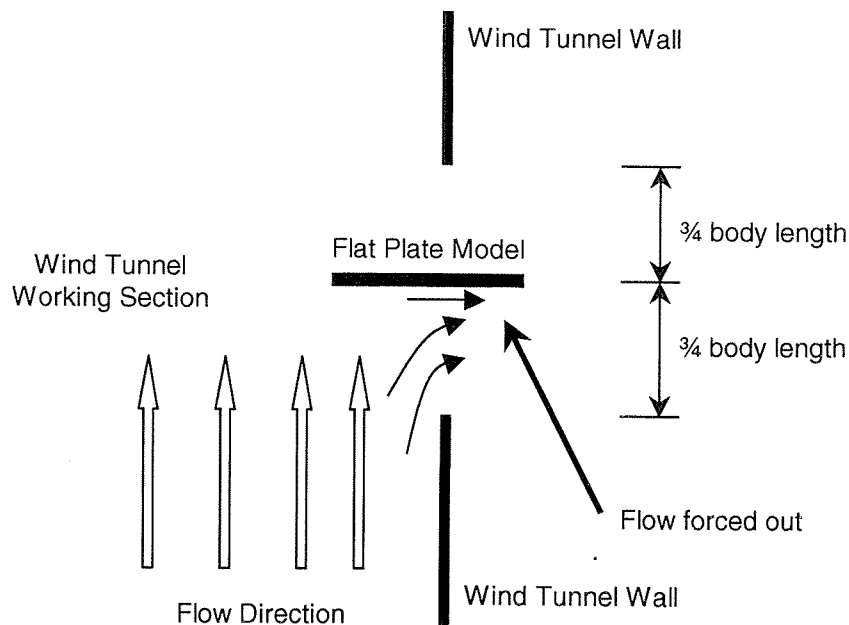


Figure 5-22 Schematic Showing Plan View of Model at Gust Exit

6. Crosswind Aerodynamics of a Sharp Edged 1-Box Model

6.1 Introduction

In this chapter, force, moment and surface static pressure data for a square, sharp edged, 1-box model is presented for the steady state and dynamic test cases. The 1-box model (Figure 4-11) is of the same length and aspect ratio as the flat plate but with a width of 200mm. Tests on the flat plate model identified the leeward face as the dominant area of transient vortex activity. This series of tests will establish if this is applicable to three-dimensional objects and if there is an increased transient response on the upper and lower faces during crosswind gust entrance and exit.

Current steady state and transient force and surface static pressure data will be compared with steady state data collected by Carr⁶⁷ using a sharp edged box model of approximately equal aspect ratio but at an increased scale (1.5 times greater). All force coefficients are lower than recorded by Carr⁶⁷ but pressure contour maps of the model surfaces show a good comparison.

As previously seen for the flat plate model, transient pressure animations show the development and collapse of vortices on the leeward face of the model resulting in maximum and minimum peak yawing moments at gust entrance and exit. Peak yawing moments on gust exit are approximately 2.5 times the steady state value.

Transient vortex activity is also present at the leading edge of the top face and the development of longitudinal vortices on the top face are seen to influence changes in pressure distribution on the leeward face.

For all dynamic tests detailed in this chapter, the track speed was approximately 13m/s and the wind tunnel speed varied to give a resultant gust velocity of 0-25° in 5° increments. Steady state tests were conducted at approximately 13m/s. and the experimental arrangement is that described in Chapter 4.

6.2 Results

6.2.1 Force and Moment Data

6.2.1.1 Steady State Tests

Figure 6-1 to Figure 6-5 show variation of the mean force and moment coefficients for 0-25° yaw and compared with data from Carr⁶⁷ using a similar aspect ratio model. All coefficients display a steady increase against yaw with the exception of the lift force and yawing moment coefficients. The lift coefficient displays a decrease in the variation with yaw angle gradient between 10 and

67. Carr G W, The Aerodynamics of Basic Shapes for Road Vehicles Part 1: Simple Rectangular Bodies, MIRA Report 1968/2, 1967

15° yaw and was also recorded by Carr⁶⁷. The yawing moment coefficient decreases up to 8° yaw and then increases approximately linearly with change in yaw angle up to 25°.

The aerodynamic force coefficients of Carr⁶⁷ are higher at lower yaw angles and become progressively greater with increasing yaw. At 25°, the values of recorded coefficients are approximately 1.4 times less than recorded by Carr⁶⁷, but in all other respects, the trends of the data are the same. The exception is the lift force coefficient that shows a greater value than Carr⁶⁷ at 0° yaw. Different Reynolds numbers used for the present tests and Carr can explain differences in magnitudes of force coefficients (see section 6.3).

6.2.1.2 Dynamic Tests

Figure 6-6 to Figure 6-10 show aerodynamic force and moment traces for the dynamic tests from 5-25° in 5° increments. Considering lift force first, there are noticeable transient responses for values of yaw greater than 20° characterised by a sharp peak on entrance to the crosswind gust and oscillation in the signature thereafter. For higher values of yaw angle there is then an increase in the lift force coefficient resulting in a second peak up until exiting the gust.

The pitching moment track signature is the hardest to interpret. For all yaw angles the change in response as the model passes from free air to the groundboard is easily definable and then there is a steady increase up to 2 body lengths into the gust followed by a small plateau in data. The aerodynamic response then increases up until exiting the gust. It can be seen that the pitching moment traces never achieve a steady state in the time taken to traverse the crosswind gust. After exiting, the change in signature is equally as puzzling with another plateau after exiting before decreasing to the before gust value.

Yawing moment traces all show a linear increase with increasing yaw and exhibit increased transient responses when entering and exiting the crosswind gust. Peak values all occur 1 body length ($x/W = 0.2$) after entering the gust and increase linearly with yaw. The peak/mean ratio has the value of 2.5 at 25° yaw. An interesting point is that whereas peak values entering the gust increase with increasing yaw, the minimum peak after exiting the gust is approximately equal for all yaw angles. Some oscillation of the yawing moment after the entrance peak is present especially at lower yaw angles and the traces do not reach a steady state before exiting the gust.

Side force dynamic traces show a small peak after entering the gust and unsteadiness thereafter and for the rolling moment signatures there is no transient response but small oscillations are present at higher values of yaw.

When comparing mean values of the dynamic force and moments (Figure 6-1 to Figure 6-5) there are slight differences for the side force and rolling moment coefficients up to 25° yaw. Mean dynamic yawing moments are all greater than the steady state values above 10° but the trend of the data is the same. Mean dynamic lift force coefficients compared with steady state values differ in magnitude but show a similar trend and even the stall identified in steady state

values between 10° and 15° is replicated. The correlation of dynamic and steady state lift force data suggests some change occurs in the flow structure between 10° and 150° . For the mean dynamic values, the changes in lift force values are relative to zero degrees yaw angle. If the mean value before subtraction of the track signature is considered, then the lift force magnitudes are comparable to the steady state values.

Values of mean dynamic pitching moment coefficients are all significantly less than the steady state values. This is in part due to the fact that the mean dynamic values are relative to zero degrees yaw angle but even then, the trend of the data is not the same. The values of mean dynamic pitching moment coefficients change little between 10° and 25° . However, the response is far from steady when the mean is taken and a comparison of peak dynamic values gives a more favourable comparison with the steady state coefficient.

6.2.2 Pressure Data

6.2.2.1 Steady State

Figure 6-11 to Figure 6-16 show steady state mean surface static pressure distributions for all faces of the sharp edged box from 0° - 25° yaw in 5° increments. At 0° yaw the flow is characterised by separation at the four leading edges resulting in large negative pressure being generated on the top, bottom, windward and leeward faces. Peak negative pressures occur for all faces at approximately $0.2 x/l$ downwind of the leading edge.

With increasing yaw angle, the separation bubble on the windward face gradually becomes more concentrated towards the leading edge resulting in an increased negative yawing moment. This is one of the reasons for the initial decrease in the change of yawing moment coefficient with increasing yaw angle identified in force measurements. By 150° the separation bubble begins to dissipate which is coincident with the increase of yawing moment. Even at the maximum yaw angle tested of 25° there is still negative pressure just behind the leading edge.

The leeward face initially shows a decrease in the negative pressure within the leading edge separation bubble with increasing yaw angle. This is coincident with the initial decrease in the coefficient value with increasing yaw angle identified in steady state yawing moment measurements. As the yaw angle increases, a region of high negative pressure is noticeable on a line of $0.2 y/h$ below the top face. This is due to the development of a longitudinal vortex as flow accelerates over the top edge.

Pressure changes on the top face are evident as skewing of the separation bubble at the leading edge and also by the development of a region of low pressure towards the rear windward quarter of the top face. As explained in the flat plate tests, this is again due to accelerating flow over the windward/top edge interface mixing with flow over the top face to produce a strong vortex.

The flow on the bottom face is the hardest to interpret due to the interference from the mounting strut. The only recognisable feature of the flow is the skewing

of the front separation bubble with increasing yaw. This is coincident with negative pressure gradually acting on the rear half of the face.

The front and rear faces do not exhibit significant changes with increasing yaw. The mean of all surface static pressure coefficients on the rear face increases linearly from a minimum value of $C_P = -0.3$ at 0° yaw to $C_P = -0.5$ at 25° yaw. As expected the change in flow field on the front face is characterised by the movement of the stagnation point towards the windward edge.

The pressure data presented by Carr⁶⁷ at 10° shows favourable agreement for all faces with the exception of the leeward. The longitudinal area of pressure on the leeward face at 0.2 y/h is not as developed in the current steady state data. At 25° yaw, there are small differences on the bottom face for the current tests but otherwise a comparison with Carr⁶⁷ is very favourable.

Force and moments integrated from the steady state surface static pressure distributions are included in the coefficient versus yaw angle data given in Figure 6-1 to Figure 6-5. All trends are similar to the steady state forces but there are slight differences in magnitudes; lift force and pitching moment are slightly higher than recorded values, side force and yawing moment is slightly lower and rolling moment approximately equal. Despite this difference the level of correlation is quite good given the coarse pressure grid used.

Comparison of steady state and mean dynamic pressure contour maps at 10° (Figure 6-17) and 20° (Figure 6-18) show that the steady state negative pressures are all greater than achieved in the dynamic tests. This is indicative of not reaching a steady state in the dynamic tests.

6.2.2.2 Transient Pressure Animation

Transient surface static pressure animations of the windward, bottom and rear faces at nominally 10° and 20° are shown in 'boxwbr10.mpeg' and 'boxwbr20.mpeg' respectively and, leeward, top and front face animations are shown in 'boxlft10.mpeg' and 'boxlft20.mpeg'. In addition, Figure 6-19 shows yawing moment data derived from integrated pressure distributions at approximately 10° and 20° and separated into leeward and windward faces. Changes in forces by integration of pressures for all 4 longitudinal faces at approximately 10° and 20° are shown in Figure 6-20.

An increased transient response at gust entrance is only evident for the top face at 20° and is responsible for the initial peak seen in the lift force coefficient dynamic traces. An examination of the top face transient animation (boxlft20.mpeg) shows that the peak on entrance is caused by an increase of pressures within the leading edge separation bubble up to $x/W = 0.3$. After this point the longitudinal vortex originating from flow accelerating over the windward/top interface begins to establish itself. Consequently a region of negative pressure develops towards the rear windward corner of the top face and an improvement in the yawing moment is made. The subsequent increase in the lift force coefficient can be explained by examination of the bottom face transient animation (boxwbr20.mpeg) and Figure 6-20. It can be seen that the flow structure over the bottom face is characterised by an initial increase in

negative pressures within the leading edge separation bubble and flow separation caused by the supporting strut. The negative pressures then gradually decrease up until exiting the gust resulting in an increased lift force coefficient.

The first point of interest on the windward face animations is a collapse of the front separation bubble just after the model enters the gust that is similar to the leeward vortex collapse identified in flat plate experiments. On exit there is a gradual return to the steady state condition.

On entrance to the gust, the negative pressure within the leeward face separation bubble gradually decreases in magnitude and the separation bubble also reduces in length. After exiting the gust the separation bubble completely collapses at approximately $0.4x/l$ downwind of the leading edge. Only after pressures on the rear half of the face have returned to the zero yaw condition does the separation bubble return at the leading edge.

Figure 6-21 and Figure 6-22 show the magnitude and location of peak pressures for the leeward face at approximately 10° and 20° . The figures show that maximum negative pressures occur $\frac{1}{2}$ body length ($x/W = 0.1$) after gust exit and at approximately $0.56 x/l$ from the trailing edge. This is coincident with the position of leeward vortex collapse identified from transient animations.

The behaviour of the windward separation bubble on entrance to the gust is comparable to the leeward separation bubble on exit and both are characterised by a significant decrease in negative pressures. It can be seen from Figure 6-19 that peaks in yawing moment at the gust entrance and exit are mainly due to pressure changes on the leeward face. Peaks in windward face yawing moment coefficient at the gust entrance are also identifiable and are due to the collapse of the windward separation bubble. The yawing moment peak on gust entrance can then be explained by a combination of:

- a collapse of the windward separation bubble
- negative pressures in the leeward leading edge separation bubble causing an increase in yawing moment before the flow has established itself over the rear

The peak in the leeward face yawing moment as the model exits the gust is due to the dissipation of pressure over the front side of the leeward face to a point located towards the upper edge (as can be seen in transient pressure animations). The front half of the face is thus subjected to decreased negative pressure but the rear half is not so affected and an improvement in the yawing moment is made.

An examination of the transient animations shows that the longitudinal vortex at the top/leeward interface is interactive with the separation bubble collapse of the leeward face and the flow structure over the top surface influences that on the leeward face. On gust entrance, the establishment of the longitudinal vortex towards the top edge of the leeward face is coincident with the sweeping movement of the separation bubble on the top face. When exiting the gust it is assumed that the top surface would react before the leeward face to any

changes in the flow field. However, an examination of the top face transient pressure animation shows this not to be the case and exhibits little change until the model has completely left the gust. The longitudinal vortex on the leeward face therefore remains and it appears that if this resulting region of strong localised pressure persists, then it is not possible for the leeward leading edge separation bubble to establish itself. Only after flow has begun to re-establish itself along the top surface does the separation bubble return at the leading edge of the leeward face.

Overall integrated forces and moments are included in Figure 6-6 to Figure 6-10 and all show very good agreement to the recorded dynamic forces. This correlation is improved over that observed for the flat plate because the 1-box model was lighter than the flat plate. Consequently, the 1-box model generates less track noise and the selected filters do not corrupt the track signature.

6.2.3 Flow Visualisation

Figure 6-23 to Figure 6-25 show surface paint flow visualisation at 0° , 10° and 20° yaw. Streak lines at 0° yaw show the separation bubble at the leading edge of the top, leeward and windward faces. Skewing of the separation bubble on the leeward and windward faces from bottom to top is identifiable as well as the extent of the separation bubble on the top surface. As the yaw angle increases, skewing of the top face separation bubble occurs and a second vortex develops along the top/windward interface. Attached flow on the top face is evident from the top/windward corner diagonally to the rear/leeward corner. A longitudinal vortex located towards the top edge of the leeward face also develops with increasing yaw angle.

Figure 6-26 shows stills taken from flow visualisation of the top and leeward faces by fluorescent tufts from $0 - 25^\circ$. On the leeward face the general pattern of fluid flow is that previously described for the flat plate tests. Flow is directed from the leading edge corners towards the centre of the leeward face and longitudinal vortices develop along the upper and lower edge with increasing yaw angle. Vortices present on the top face at the leading edge and windward interface can also be identified.

6.3 Discussion

6.3.1 Previous Work

The most complete data set for bluff bodies of this type is by Carr⁶⁷ who found that the aerodynamic force and moment coefficients are strongly altered with increases in yaw angle with the exception of the yawing moment coefficient. This is due the side force acting to the rear of the midpoint at low angles of yaw and only slightly forward at a yaw angle of 25° . Surface static pressure measurements by Carr showed that the flow field of the sharp edged 1-box model is characterised by long separation bubbles from all 4 leading edges and the changes with yaw angle are that previously described. The force data of Carr and the present research shows good agreement in the trends of the data with changes in yaw angle but force coefficient magnitudes are higher in Carr.

This is explained by the different scales of models used and hence differing Reynolds number simulation.

The Reynolds number is a measure of the ratio of inertial to viscous fluid forces acting on a body and correct modeling is important for all scale model wind tunnel tests. At abrupt changes in flow direction the inertial force is generally greater than any viscous force and flow will separate at these points. The strength of the resultant separation bubble and reattachment length is dependent upon the inertial force and hence fluid velocity. At very low Reynolds numbers flow separation increases with increasing fluid velocity up to a point when the separation length remains constant. This flow regime is termed subcritical and persists up to a critical Reynolds number. Separation length is unstable around the critical Reynolds number until the transcritical flow regime is established. In the trans-critical regime, the separation length decreases significantly from the sub critical value.

Figure 6-27 displays results of Reynolds number sensitivity tests on the sharp edged box model at 5° yaw angle. The aerodynamic force and moment coefficients were recorded at several increments between a wind tunnel velocity of 2 and 17m/s. This corresponds to a Reynolds number based on the square root of frontal area of between 0.3×10^5 and 2.4×10^5 . Sudden changes in the coefficients occur up to $Re = 1 \times 10^5$ but then there is negligible change up to $Re = 2.9 \times 10^5$. Tests on the sharp edged box model were conducted at approximately 13m/s corresponding to a Reynolds number of 1.8×10^5 and within the subcritical regime. It can be concluded therefore that the sharp edged box and flat plate models are insensitive to changes in Reynolds number in the subcritical regime.

Extrapolation of these results to full scale Reynolds numbers in the transcritical regime is not straightforward. Cooper⁶⁸ conducted similar tests on box models up to much higher Reynolds numbers and found that side force and rolling moment are insensitive to changes in Reynolds number but that lift force and yawing and pitching moments were less so. A comparison of the Reynolds number sensitivity tests of Cooper and present data is included in Figure 6-28. Initial differences in lift force and pitching moment coefficients can be explained by a different ground clearance used by Cooper. As the flow approaches the transcritical regime at higher Reynolds number ($> 1 \times 10^6$), Cooper found that the yawing moment decreased steadily, lift force increased steadily and pitching moment initially decreased before attaining a stable value. On this evidence the present results cannot be extrapolated to full scale.

Computational experiments using large eddy simulation by Yu⁶⁹ looked at the influence aspect ratio had upon the pressure distribution around a rectangular body in a 2 dimensional flow field. It was found that an increase in streamwise length was coincident with reattachment of flow along the streamwise faces with

68. Cooper K R, The Effect of Front-Edge Rounding and Rear-Edge Shaping on the Aerodynamic Drag of Bluff Vehicles in Ground Proximity, SAE 850288, 1985

69. Yu D and Kareem A, Two-Dimensional Simulation of Flow Around Rectangular Prisms, JWEIA Vol. 62, pp. 131-161, 1996

reattachment occurring at or around an aspect ratio of 1:2. This is contrary to the data of Carr and of the present research where reattachment is well established at an aspect ratio of 1:2.4. In addition Yu fails to predict the magnitudes of peak negative pressures at the leading edges of the streamwise faces.

Russell⁷⁰ conducted stability studies on rectangular bodies of varying aspect ratio. The magnitudes and variation with increasing yaw angle of side force and yawing moment coefficients are approximately equal to the current research. Russell also wanted to determine the flow field characteristics on the leeward and upper surfaces and conducted surface paint flow visualisations tests to determine node and saddle points of the vortex structures. 3 patterns of flow were identified for the leeward surface. At 0° yaw, the flow patterns are that as previously described; flow separates at the leading edge and reattaches to form a separation bubble. By 3° yaw this pattern is replaced by a flow structure dominated by attachment lines running from towards the leading edge corners to the rear, and separation lines along the streamwise edges and center line. Nodes are identified at approximately midpoint in length and ¼ and ¾ distance in height. From 3° to 8°, the attachment lines move progressively towards the centre line and the nodes become unified at the centreline slightly to the rear of midpoint. This final flow structure was observed up to 15° yaw angle and is similar to that previously described for the current work. Flow visualisation studies by Russell of the top surface are also in close agreement with the current tests.

Yoshida⁷¹ has conducted transient experiments on vehicle like shapes using a similar experimental arrangement as that used here. However, the angles of yaw presented are much higher than that experienced in real life conditions, and none of the work can be used for a direct comparison here. Of interest though is that the pattern of force coefficient dynamic traces are very similar, particularly the yawing moment which exhibits transient peaks and troughs at the gust entrance and exit. These peaks are also evident in data published by Baker⁷² on his work on the transient response of passenger trains. Baker also confirms the unsteadiness of the lift force coefficient and the 2-peak behaviour (Figure 6-6) is also in evidence, though appreciably at much higher yaw angles.

6.3.2 Comparison with Flat Plate Model

The most obvious change between the flow fields of the flat plate and sharp edged 1-box model is a decrease in negative pressures on the leeward and windward faces. This combined with a movement of the centre of pressure towards mid-axis also results in lower yawing moment coefficients. As like the flat plate, the transient response of the sharp edged 1-box model is most

70. Russell J R, Flow and Stability Studies on Models of Cuboids with ratios of Dimensions Resembling those of Commercial Road Vehicles and Buses, 4th International Colloquium in Industrial Aerodynamics, pp. 75-87

71. Yoshida Y, Muto S and Imaizumi T, Transient Aerodynamic Forces and Moments on Models of Vehicles Passing Through Crosswind, SAE 770391, 1977

72. Baker C J, Train Aerodynamic Forces and Moments from Moving Model Experiments, JWEIA Vol. 24, pp. 227-151, 1986

significant on exiting the gust and characterised by the collapse of the leeward separation bubble and resulting in high yawing moments. The collapse of the windward separation bubble on gust entrance is now identifiable and this also contributes to the peak in yawing moment at the gust entrance.

In the flat plate model tests, mean dynamic side force and yawing moment coefficients are all lower than the steady state values. This was attributed to not reaching a steady state during the time taken to traverse the crosswind gust. For the sharp edged 1-box model tests the mean dynamic coefficients are again lower with the exception of the yawing moment coefficient. This is not as unusual as it first seems because instead of approaching a higher value in the flat plate tests the sharp 1-box model approaches a lower value of steady state yawing moment after the initial peak at the gust entrance.

6.4 Conclusions

From the combined force, surface static pressure and flow visualisation data of a sharp edged 1-box model, the following conclusions can be made.

1. All steady state force and moment coefficients increase approximately linearly with yaw with the exception of the yawing moment coefficient.
2. The steady state yawing moment coefficient initially decreases with increasing yaw before reaching a positive value at about 10° . This is caused by a combination of:
 - A sustained windward face leading edge separation bubble
 - An initial decrease in negative pressures within the leeward face leading edge separation bubble
3. Steady state flow structure is characterised by long separation bubbles on all 4 longitudinal edges. With increasing yaw, the following aspects of fluid flow are identifiable on each face:
 - Windward - Decrease of separation bubble length and negative pressure coefficients within the separation bubble, movement of separation bubble towards the leading edge
 - Leeward - Increase of separation bubble length and decrease of negative pressure coefficients within the separation bubble, development of longitudinal vortices along upper and lower edges (upper stronger than lower)
 - Top - Skewing of separation bubble towards leeward face, decrease in negative pressure coefficients within the separation bubble, longitudinal vortex develops along top/windward interface
4. Dynamic testing produces peaks in yawing moment coefficient approximately 2.5 times greater than observed for the steady state condition
5. The yawing moment peak on gust entrance can be explained by a combination of

- A collapse of the windward separation bubble
 - Negative pressures in the leeward leading edge separation bubble causing an increased yawing moment before the flow has established itself over the rear half of the model.
6. The peak in the leeward face yawing moment as the model exits the gust is due entirely to the collapse of leeward separation bubble to a point located towards mid axis and the upper edge
 7. The double peak behaviour of the lift force coefficient when entering a transient crosswind gust can be explained by:
 - Peak negative pressures within the leading edge separation bubble before the longitudinal vortex originating from the windward face has been established
 - A decrease in negative pressures within the leading edge separation bubble of the bottom face
 8. The mechanism of leeward separation bubble collapse identified in this series of tests is seen to be interactive with the flow structure on the top face and requires further investigation

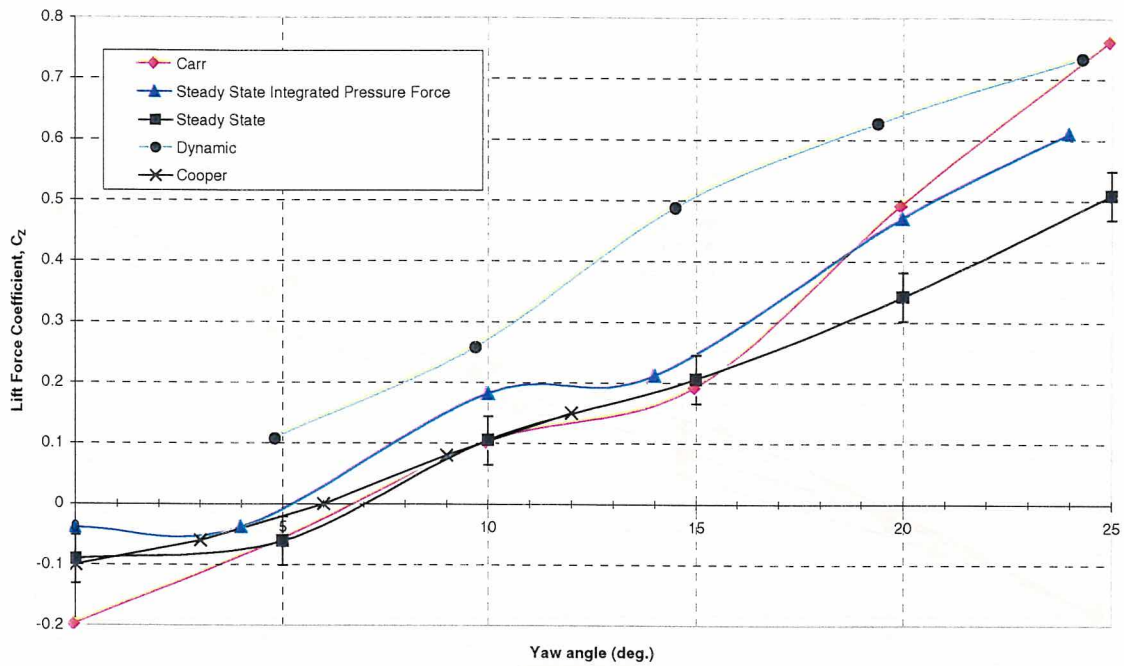


Figure 6-1 Variation of Lift Force Coefficient with Yaw Angle for Sharp Edged 1-Box Model

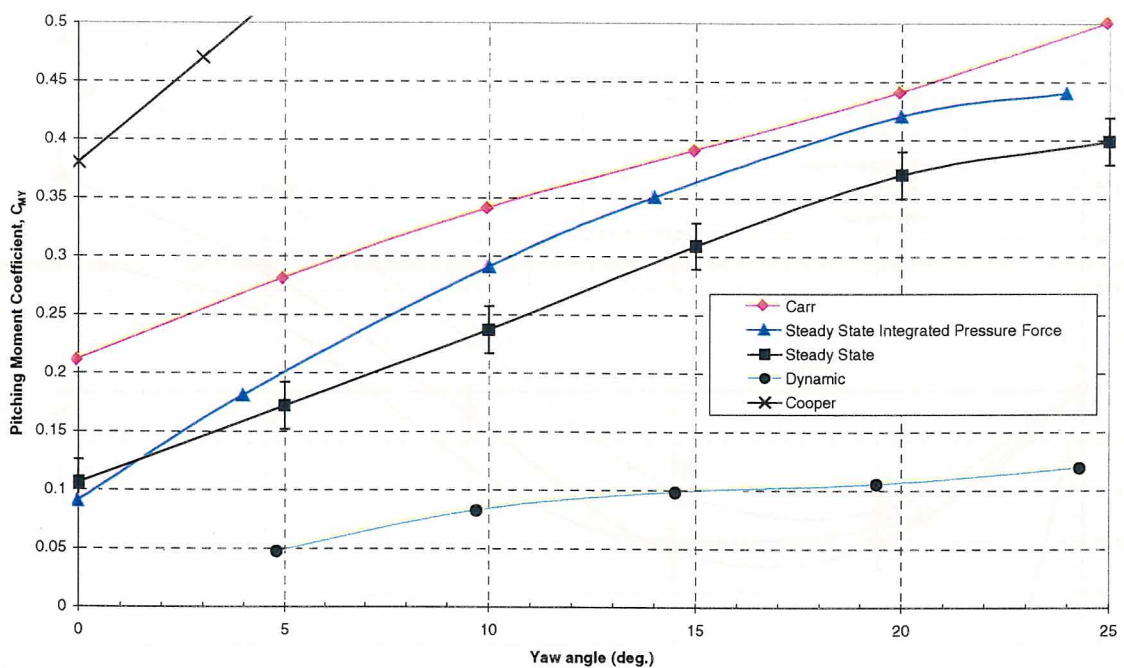


Figure 6-2 Variation of Pitching Moment Coefficient with Yaw Angle for Sharp Edged 1-Box Model

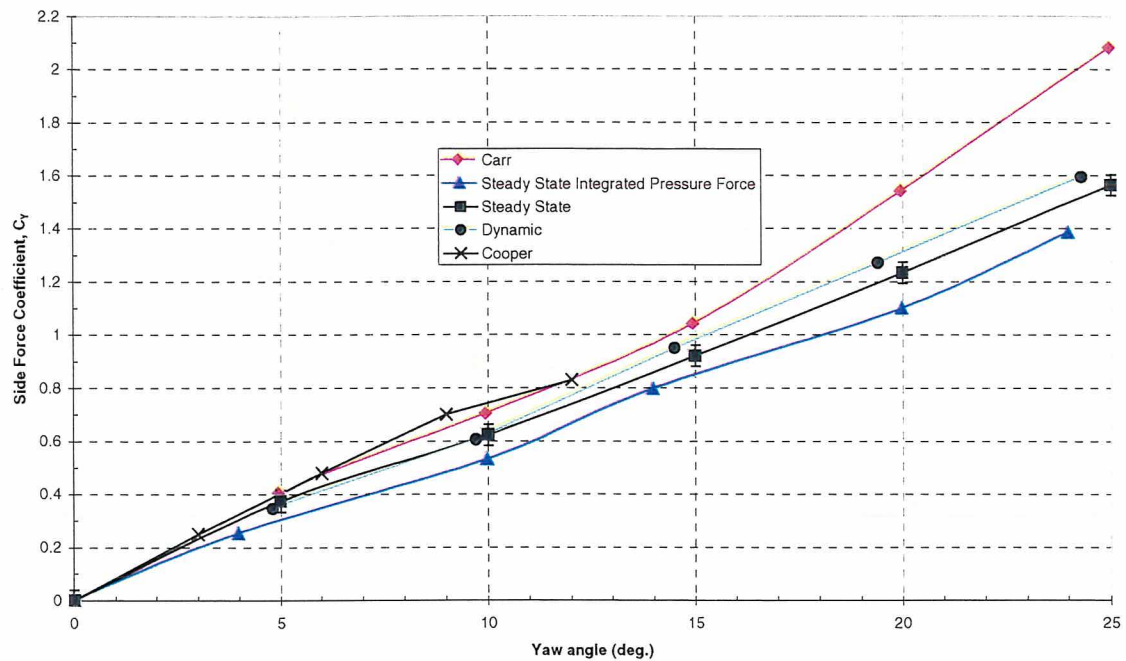


Figure 6-3 Variation of Side Force Coefficient with Yaw Angle for Sharp Edged 1-Box Model

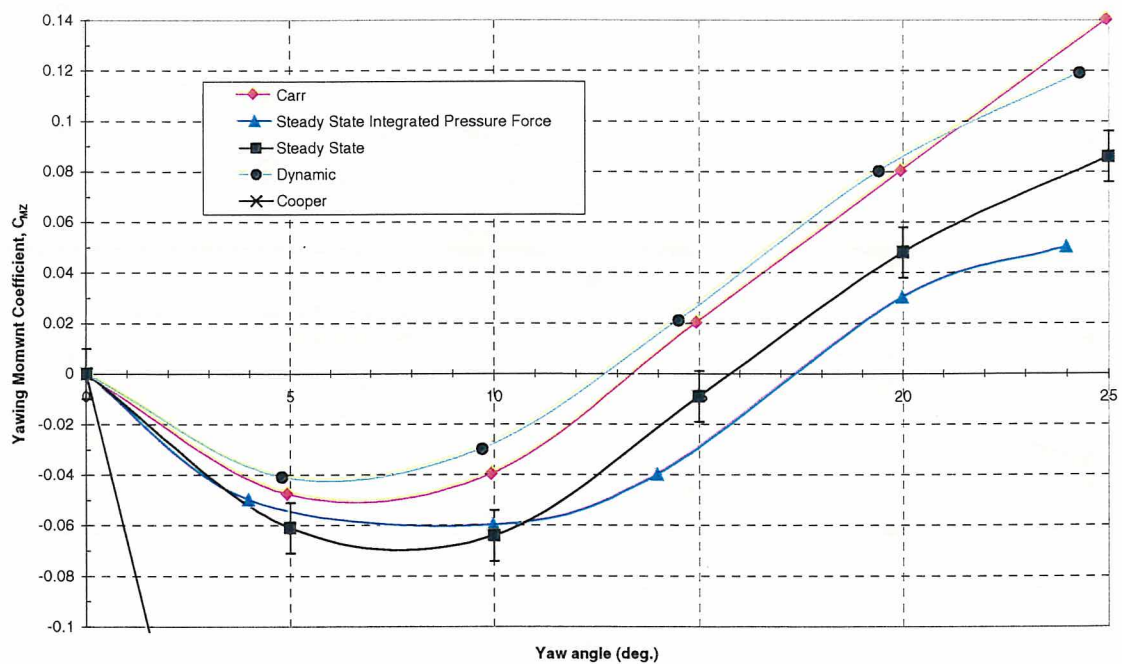


Figure 6-4 Variation of Yawing Moment Coefficient with Yaw Angle for Sharp Edged 1-Box Model

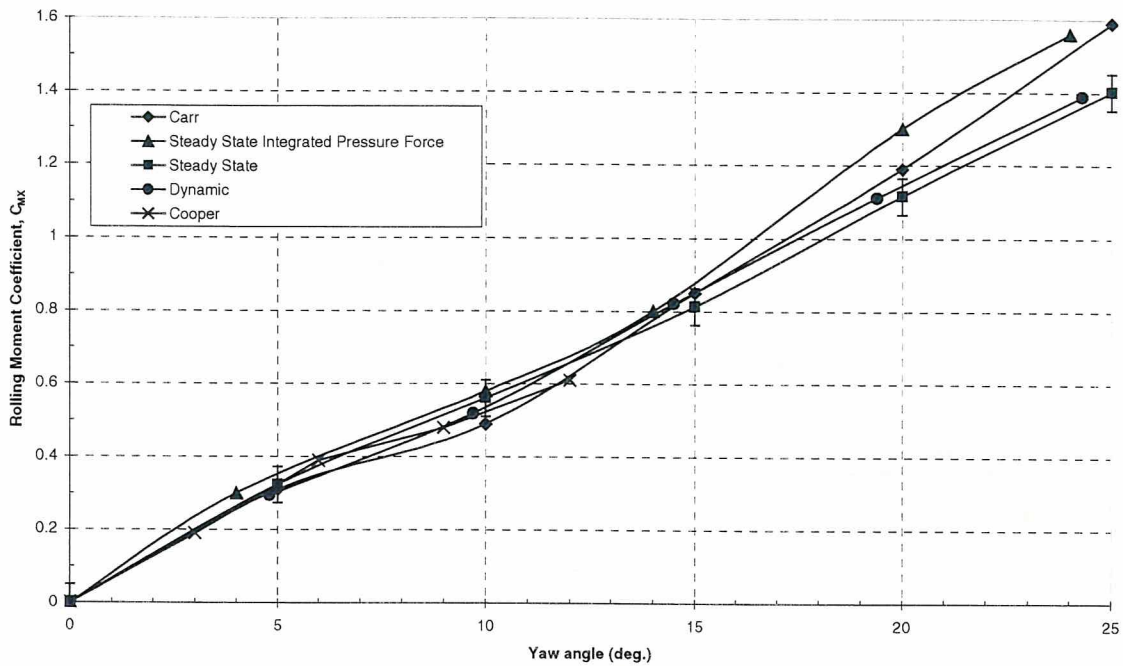


Figure 6-5 Variation of Rolling Moment Coefficient with Yaw Angle for Sharp Edged 1-Box Model

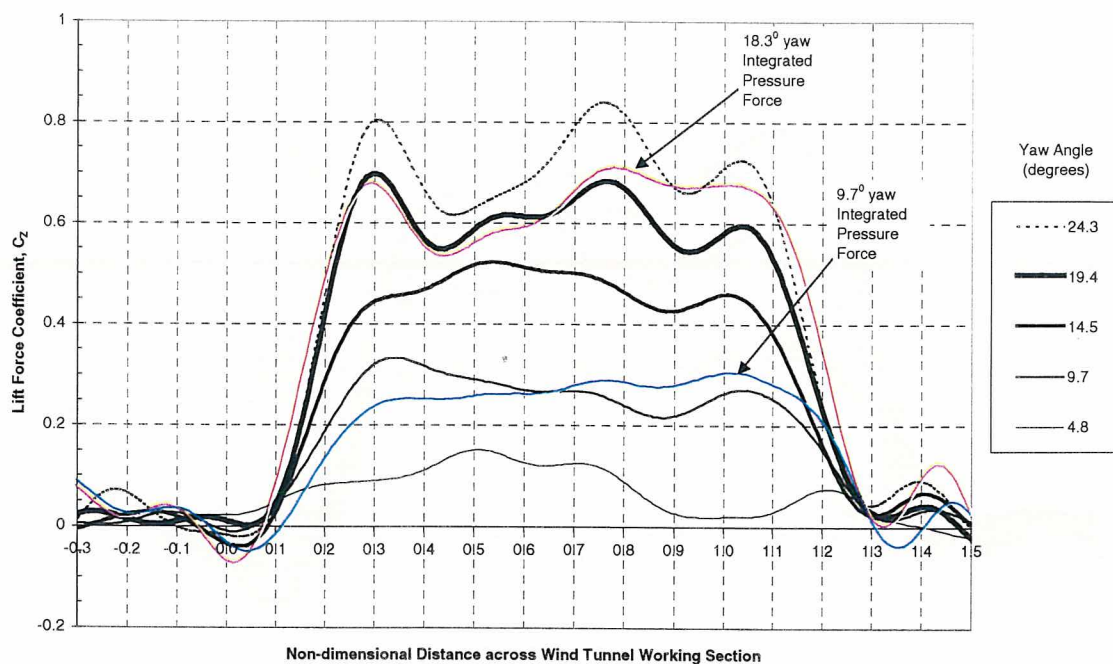


Figure 6-6 Sharp Edged 1-Box Model Lift Force Coefficient Dynamic Traces for Various Yaw Angles

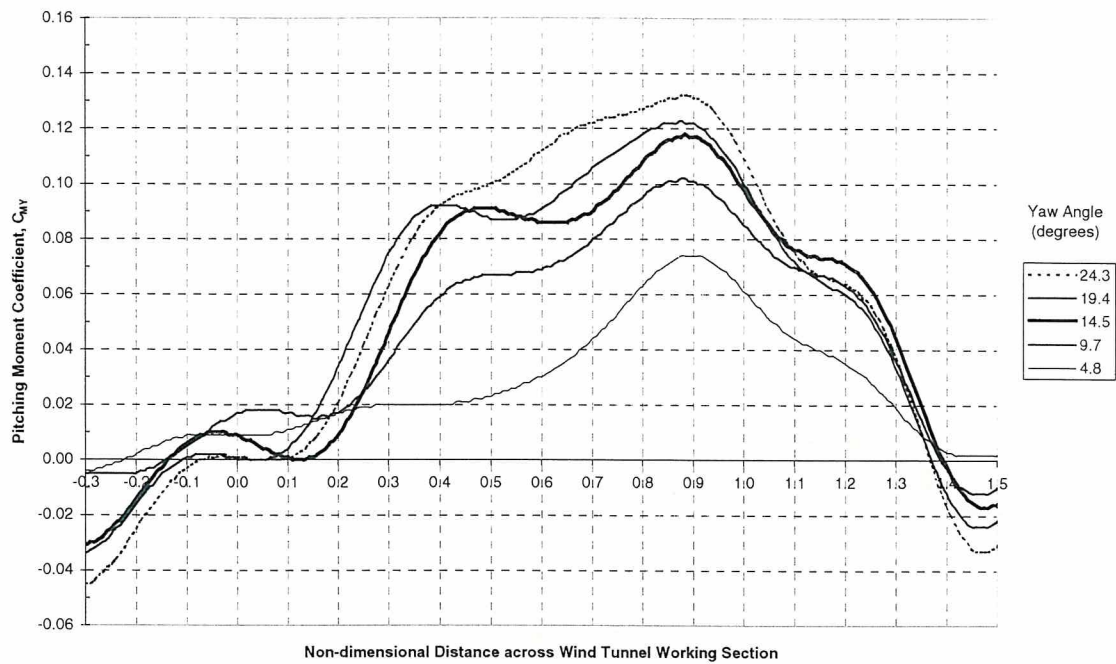


Figure 6-7 Sharp Edged 1-Box Model Pitching Moment Coefficient Dynamic Traces for Various Yaw Angles

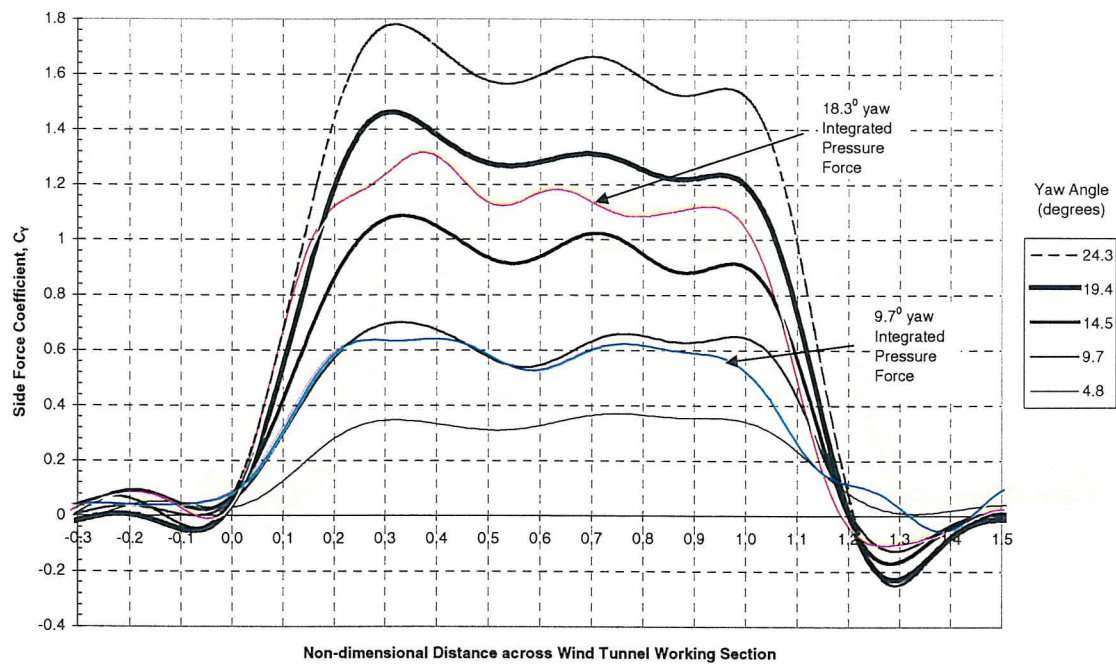


Figure 6-8 Sharp Edged 1-Box Model Side Force Coefficient Dynamic Traces for Various Yaw Angles

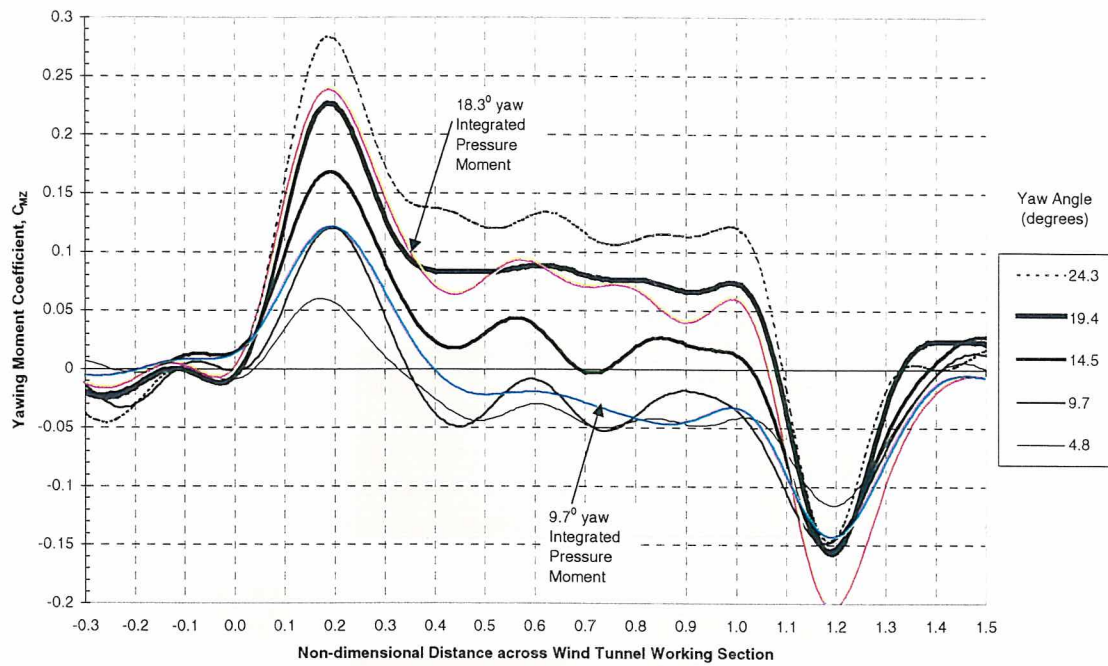


Figure 6-9 Sharp Edged 1-Box Model Yawing Moment Coefficient Dynamic Traces for Various Yaw Angles

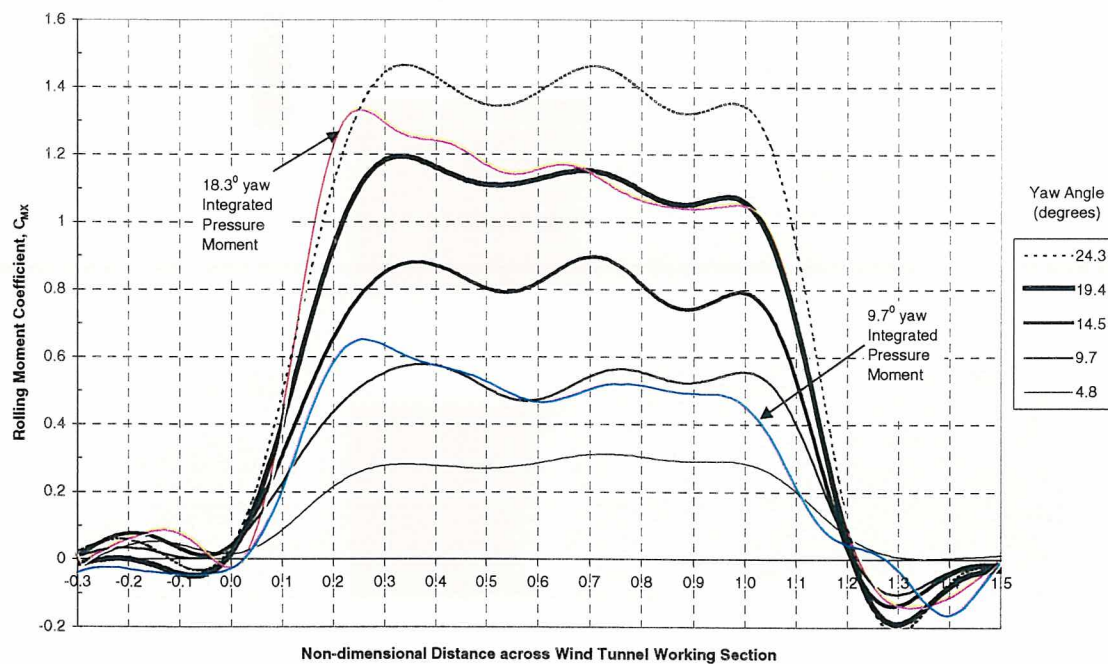


Figure 6-10 Sharp Edged 1-Box Model Rolling Moment Coefficient Dynamic Traces for Various Yaw Angles

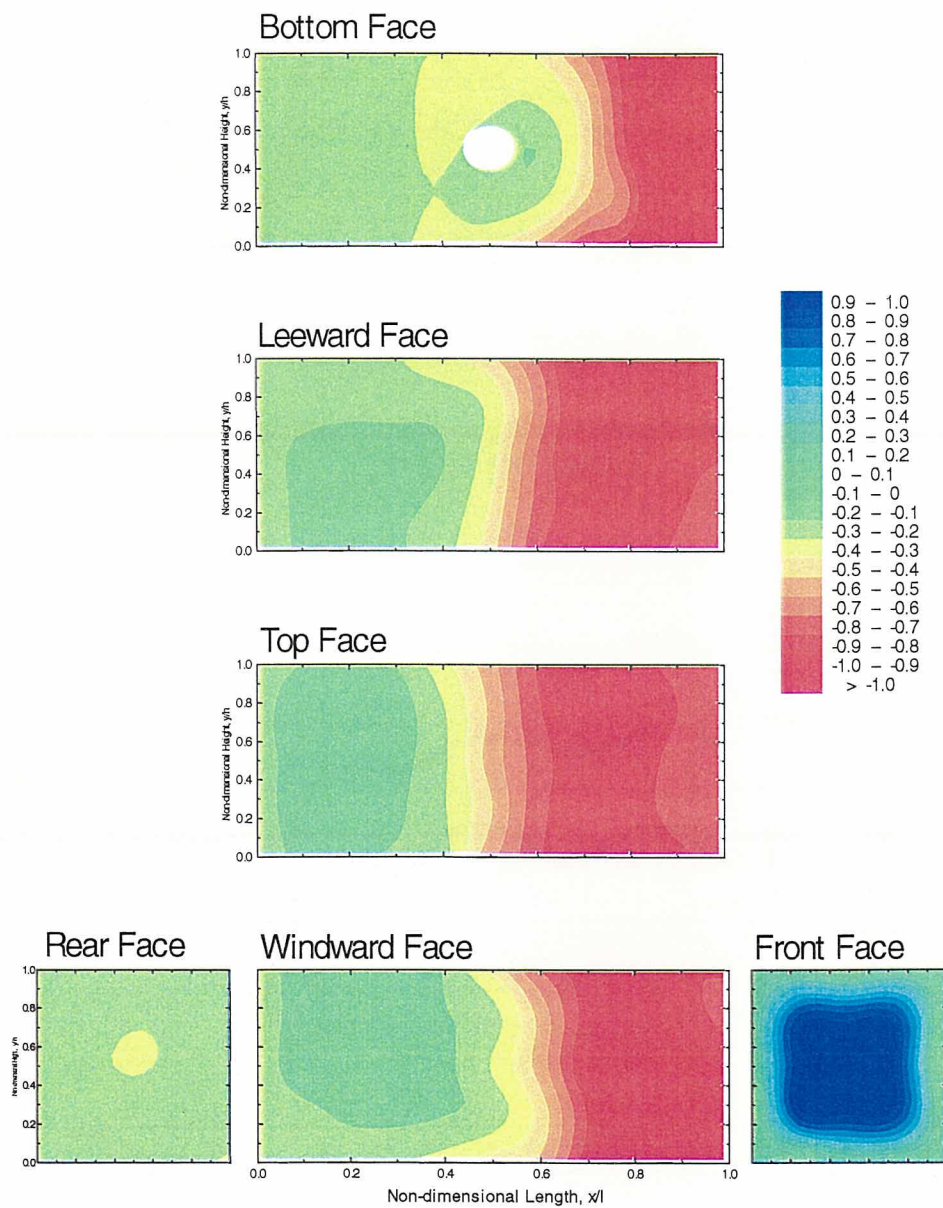


Figure 6-11 Sharp Edged 1-Box Model Steady State Pressure Map at 0° Yaw. Leading Edge to Left of Page

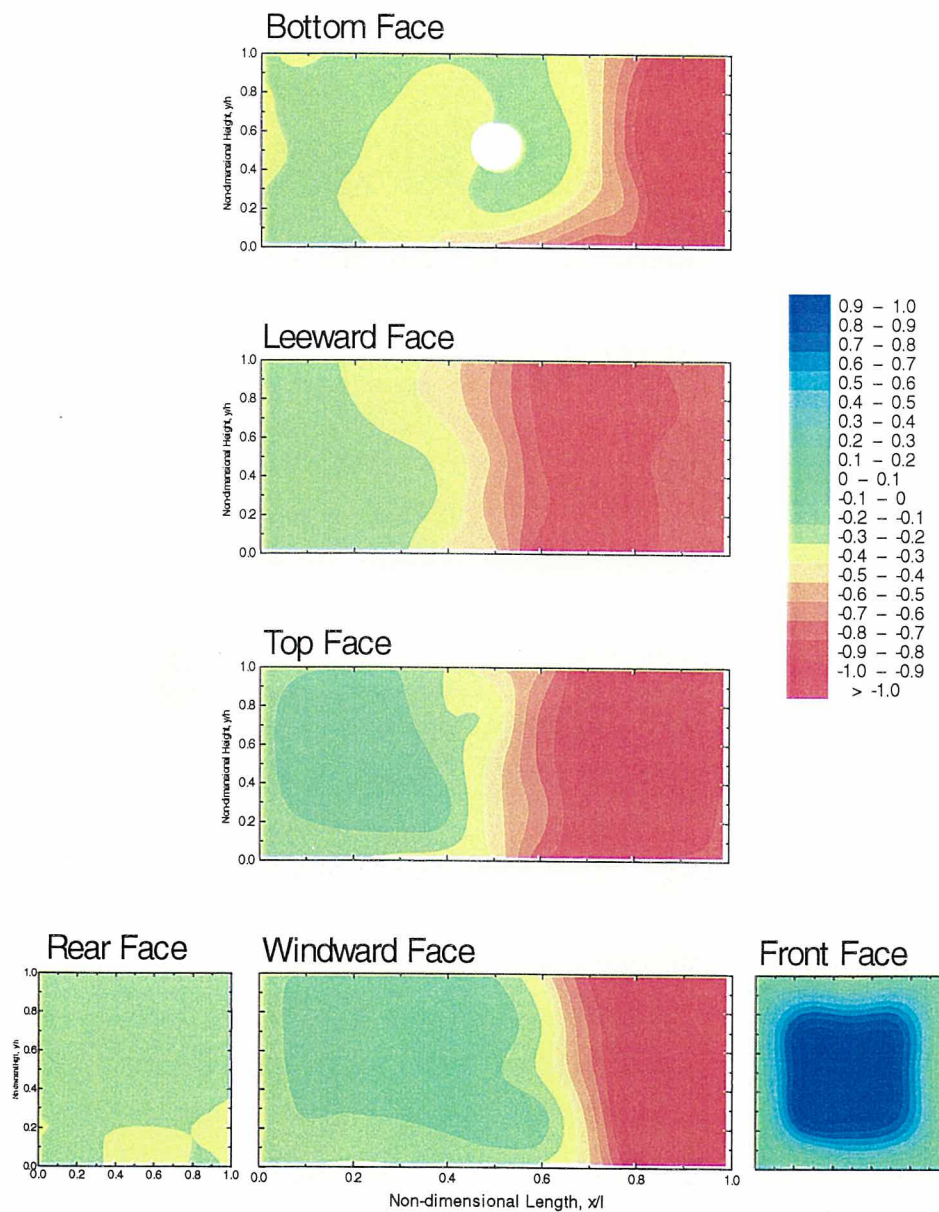


Figure 6-12 Sharp Edged 1-Box Model Steady State Pressure Map at 5° Yaw. Leading Edge to Left of Page

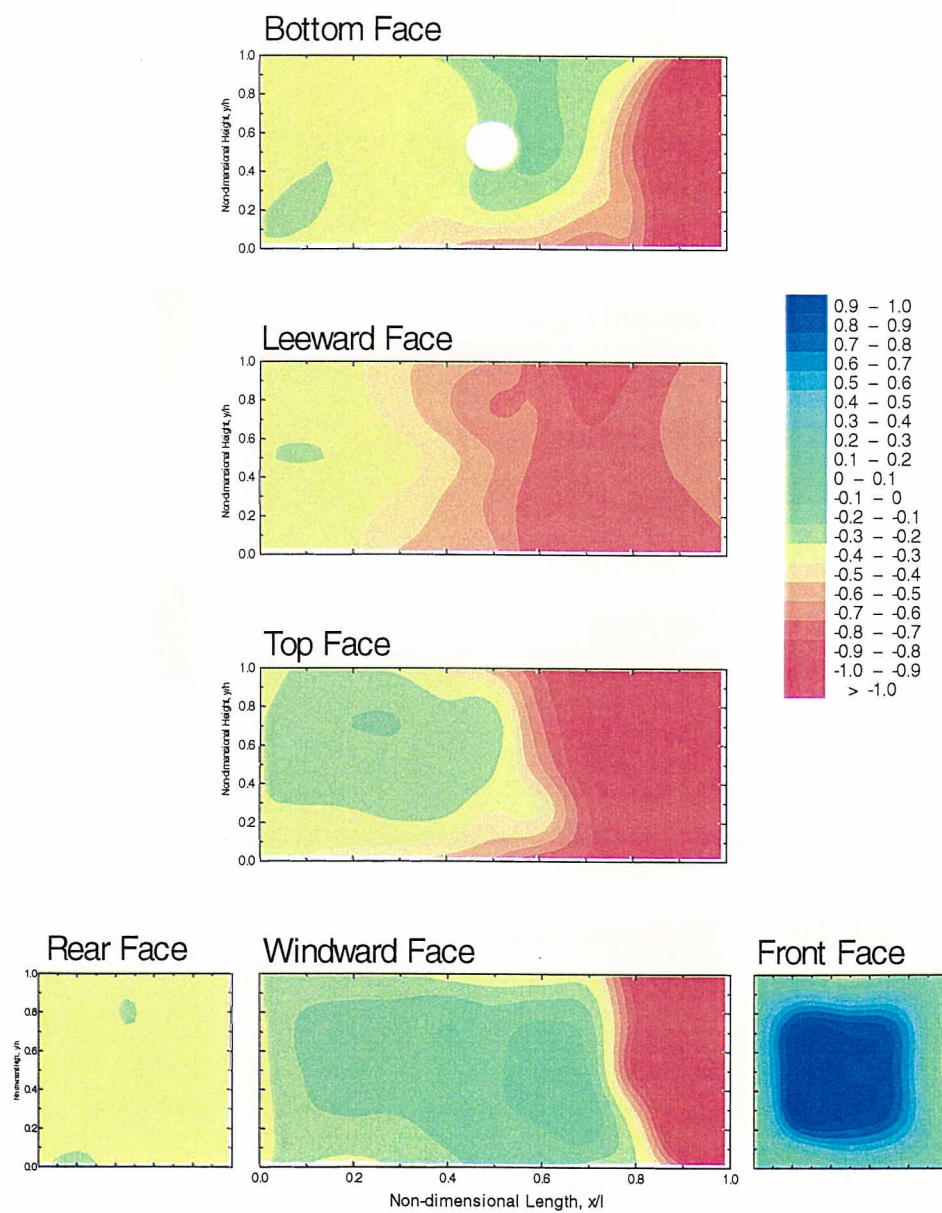


Figure 6-13 Sharp Edged 1-Box Model Steady State Pressure Map at 10° Yaw. Leading Edge to Left of Page

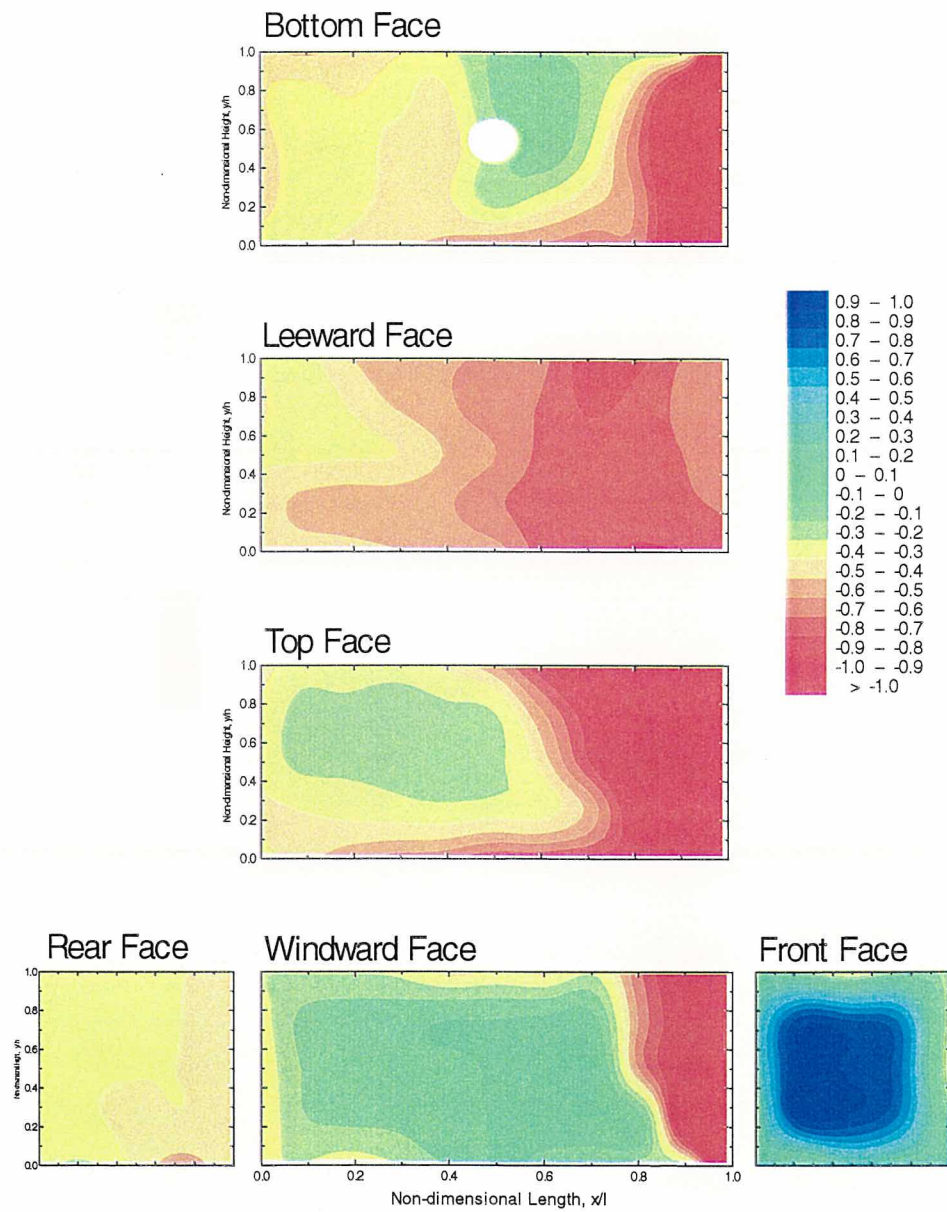


Figure 6-14 Sharp Edged 1-Box Model Steady State Pressure Map at 15° Yaw. Leading Edge to Left of Page

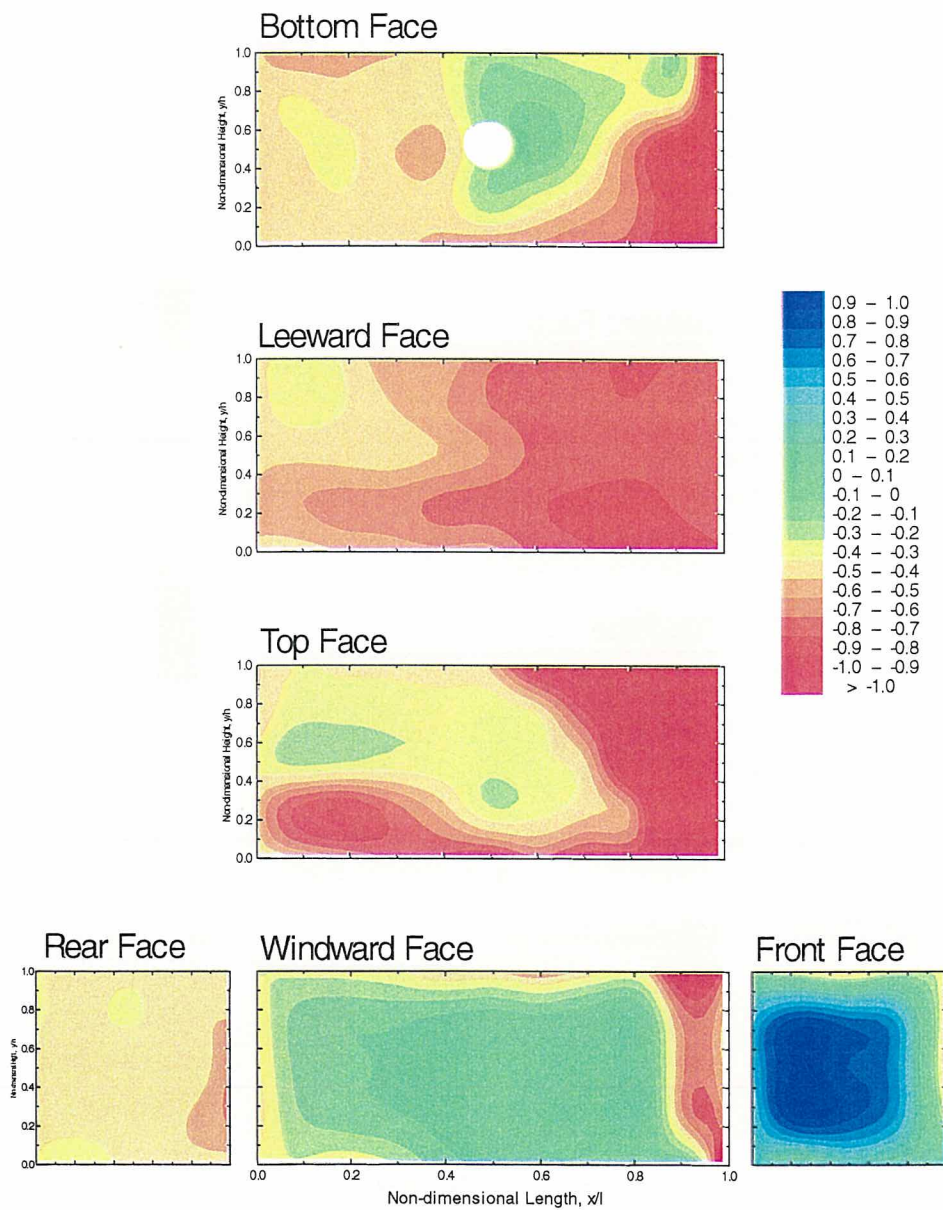


Figure 6-15 Sharp Edged 1-Box Model Steady State Pressure Map at 20° Yaw. Leading Edge to Left of Page

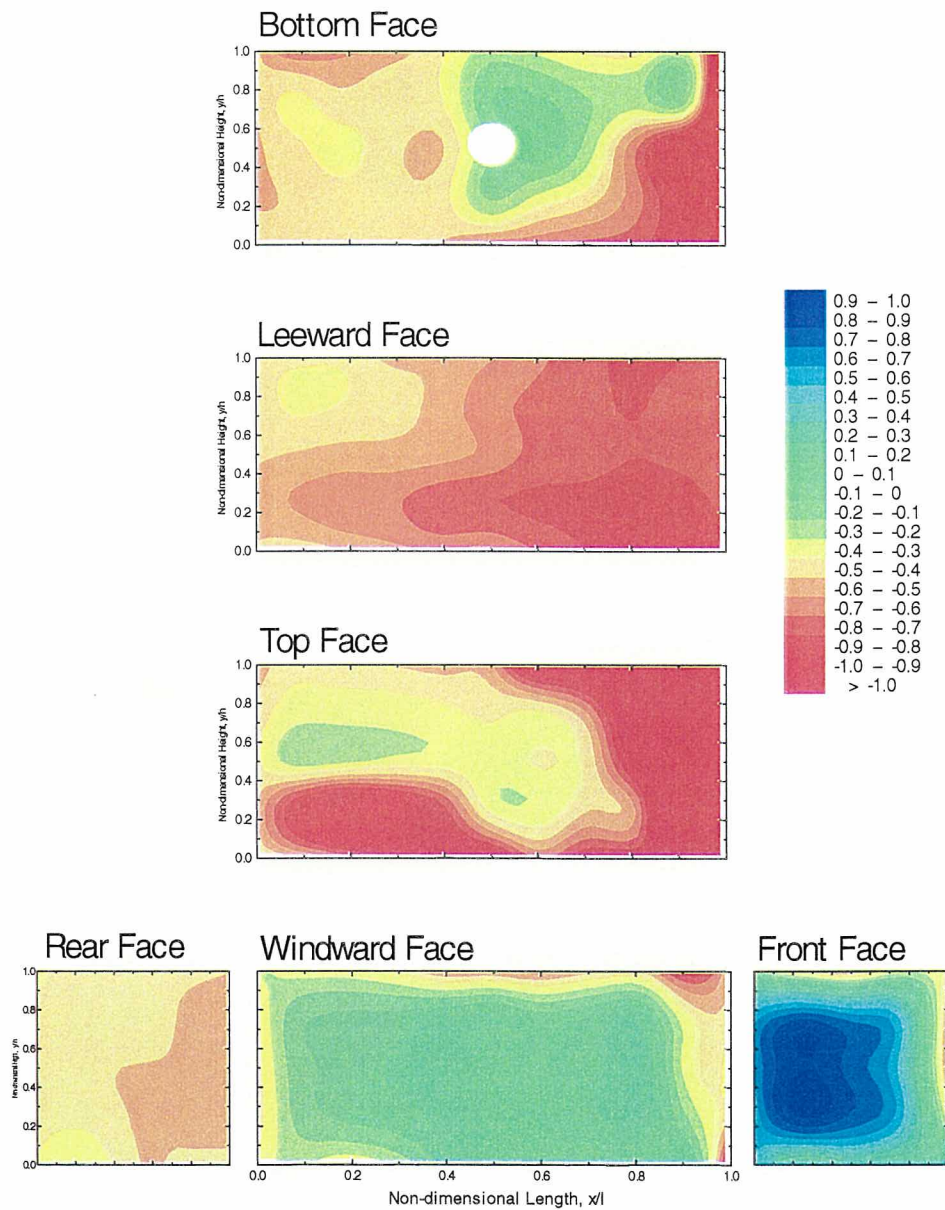


Figure 6-16 Sharp Edged 1-Box Model Steady State Pressure Map at 25° Yaw. Leading Edge to Left of Page

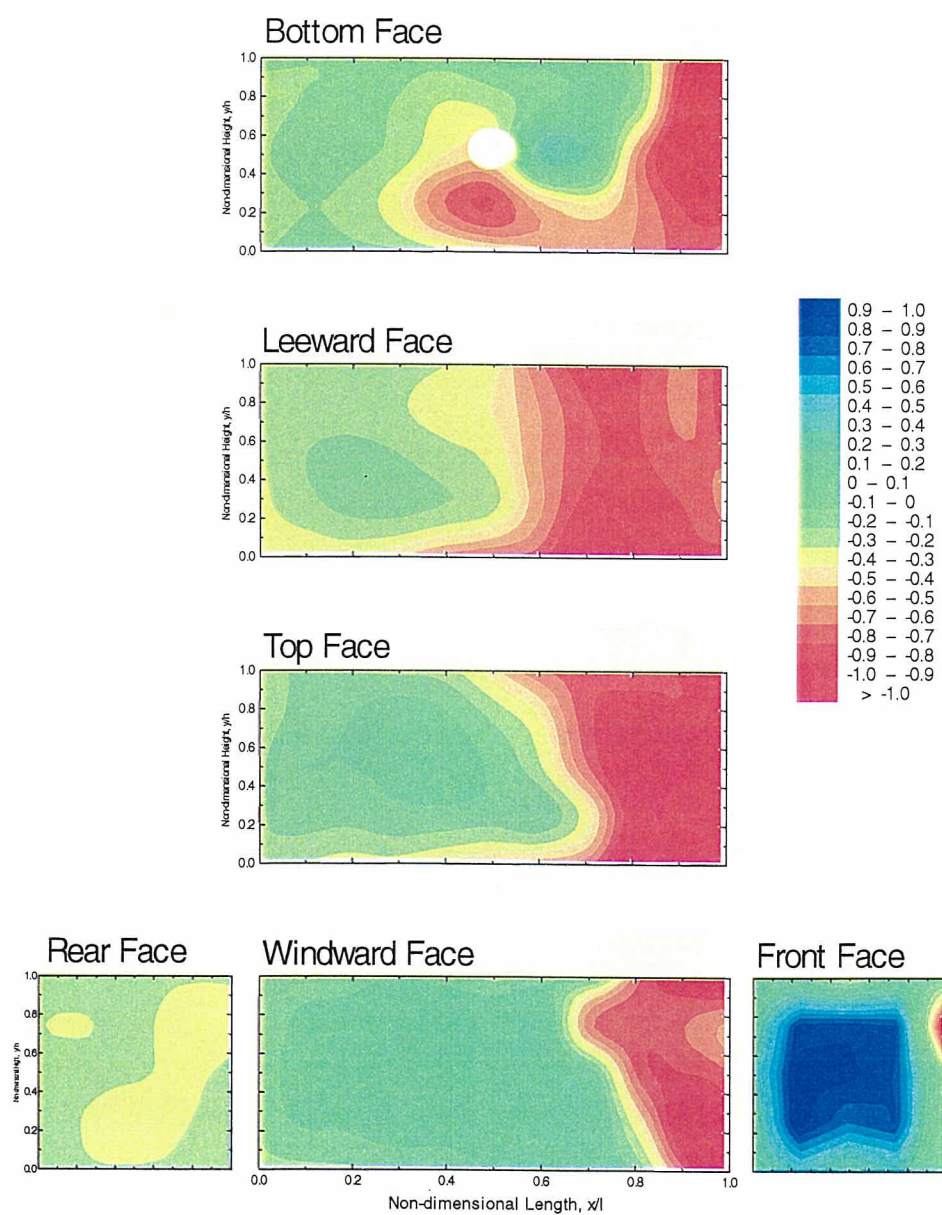


Figure 6-17 Sharp Edged 1-Box Model Mean Dynamic Pressure Map at 10° Yaw. Leading Edge to Left of Page

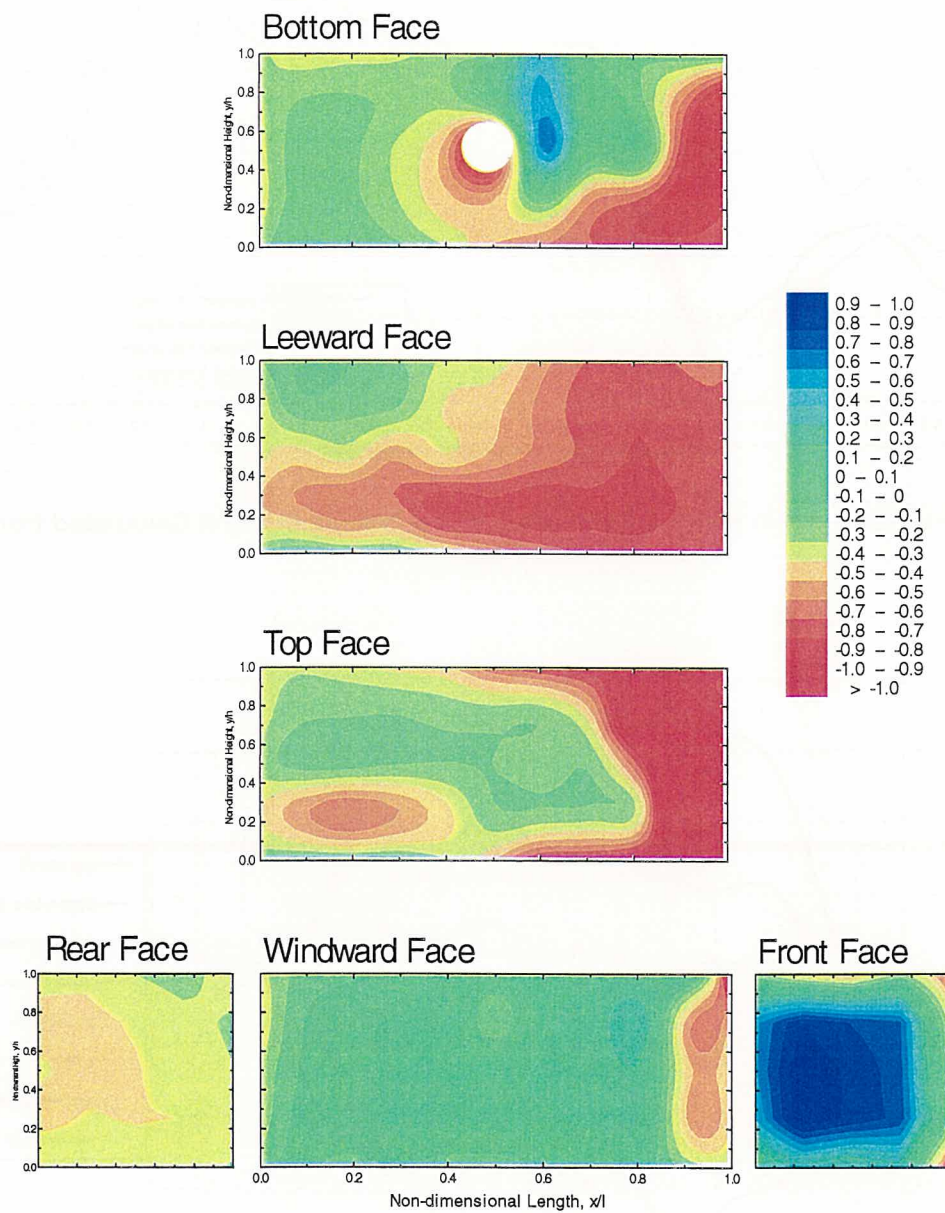


Figure 6-18 Sharp Edged 1-Box Model Mean Dynamic Pressure Map at 20° Yaw. Leading Edge to Left of Page

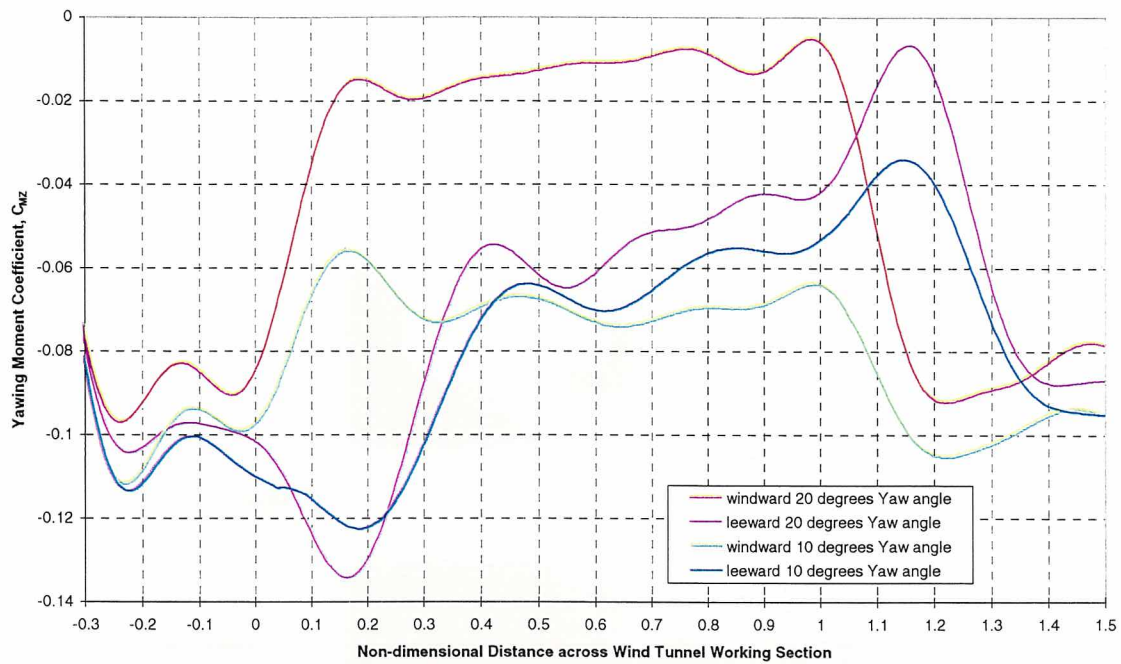


Figure 6-19 Changes in Sharp Edged 1-Box Model Yawing Moment Calculated from Dynamic Pressures

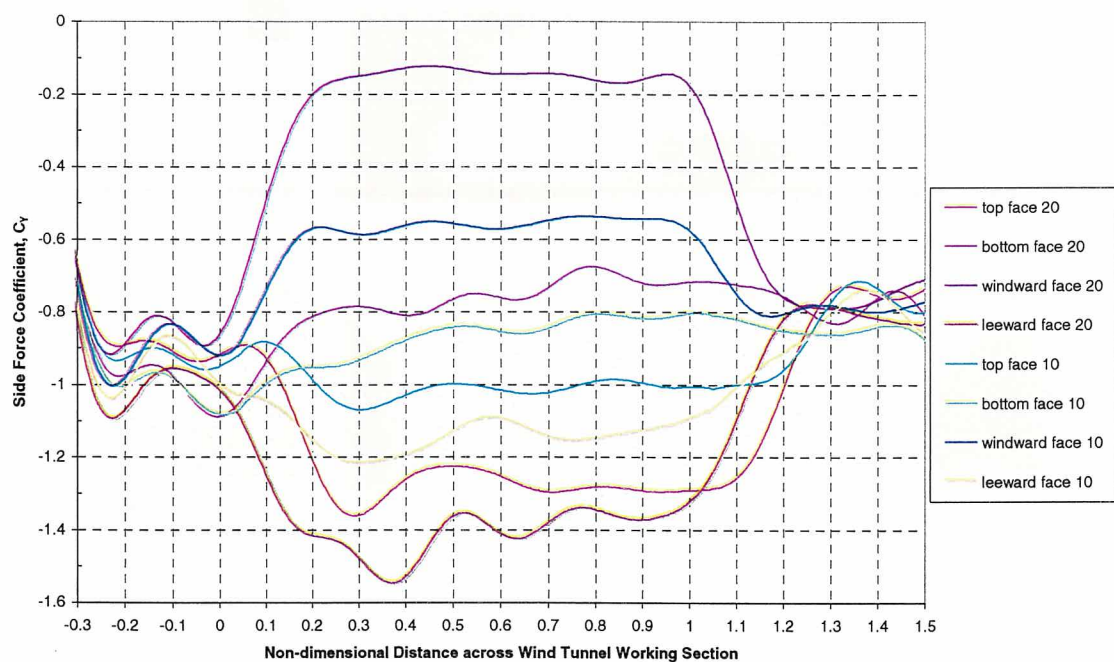


Figure 6-20 Changes in Sharp Edged 1-Box Model Side Force Calculated from Dynamic Pressures

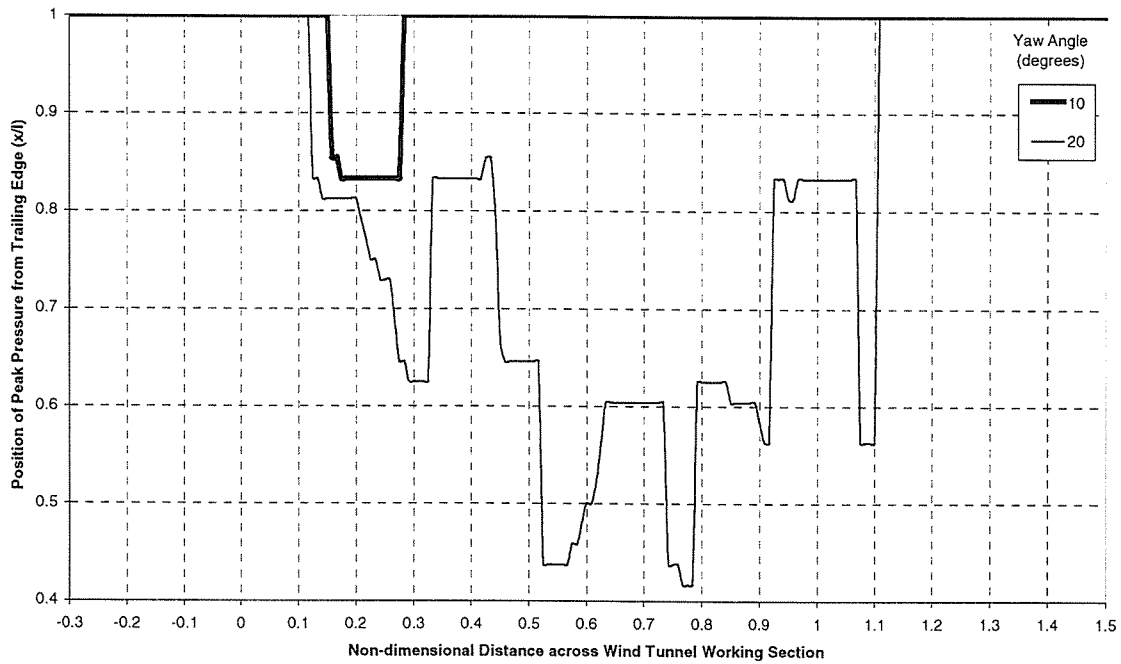


Figure 6-21 Positions of Transient Peak Pressures on Leeward Face for Dynamic Pressure Tests

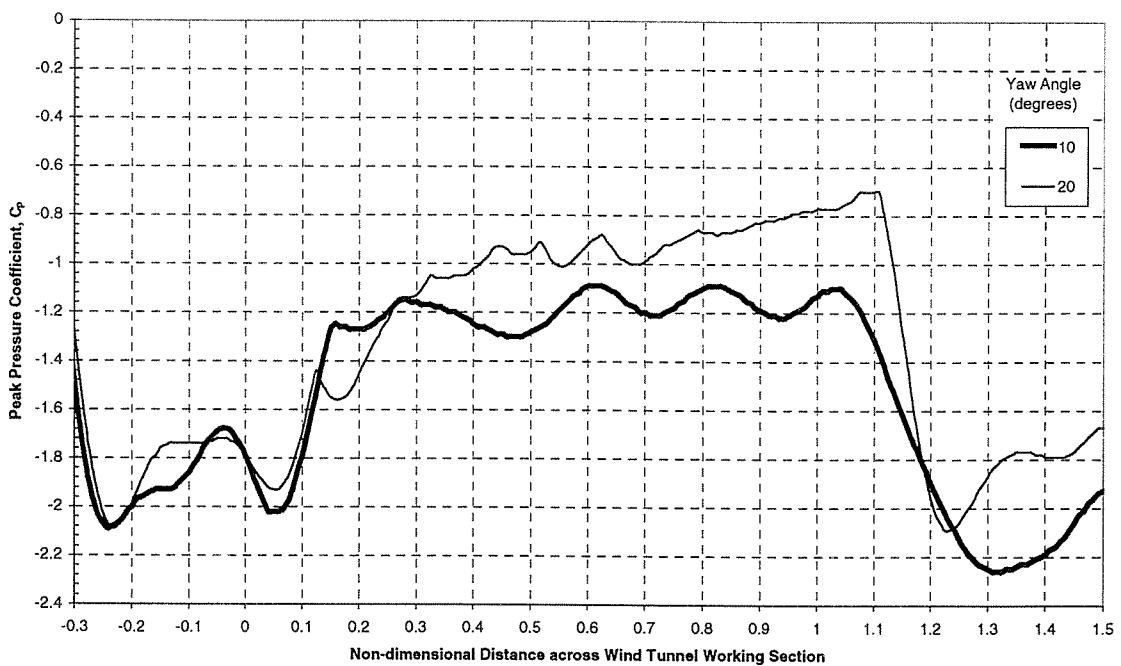


Figure 6-22 Sharp Edged 1-Box Model Transient Peak Pressures on Leeward Face for Dynamic Pressure Tests

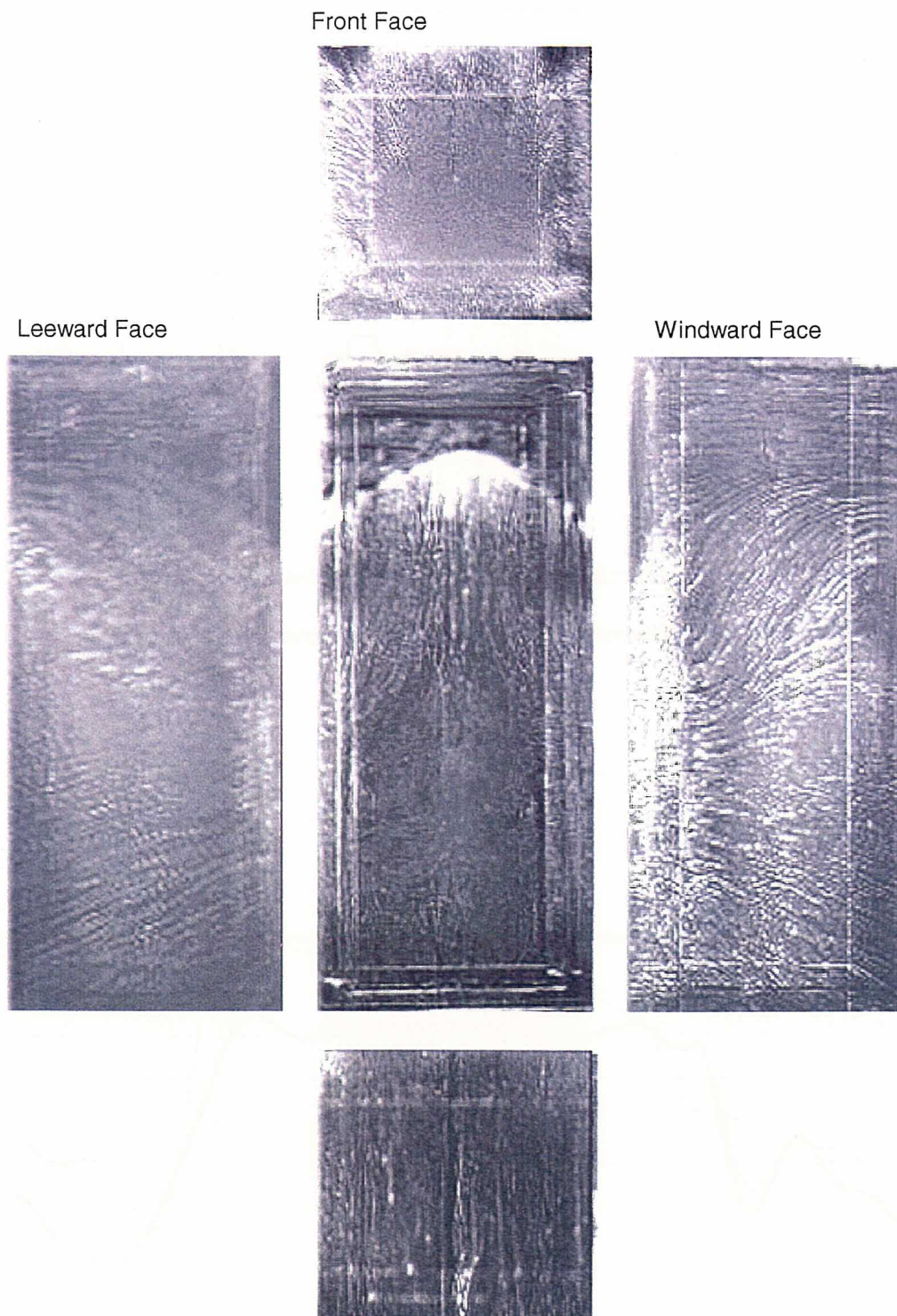


Figure 6-23 Sharp Edged 1-Box Model Surface Paint Flow Visualisation at 0° yaw

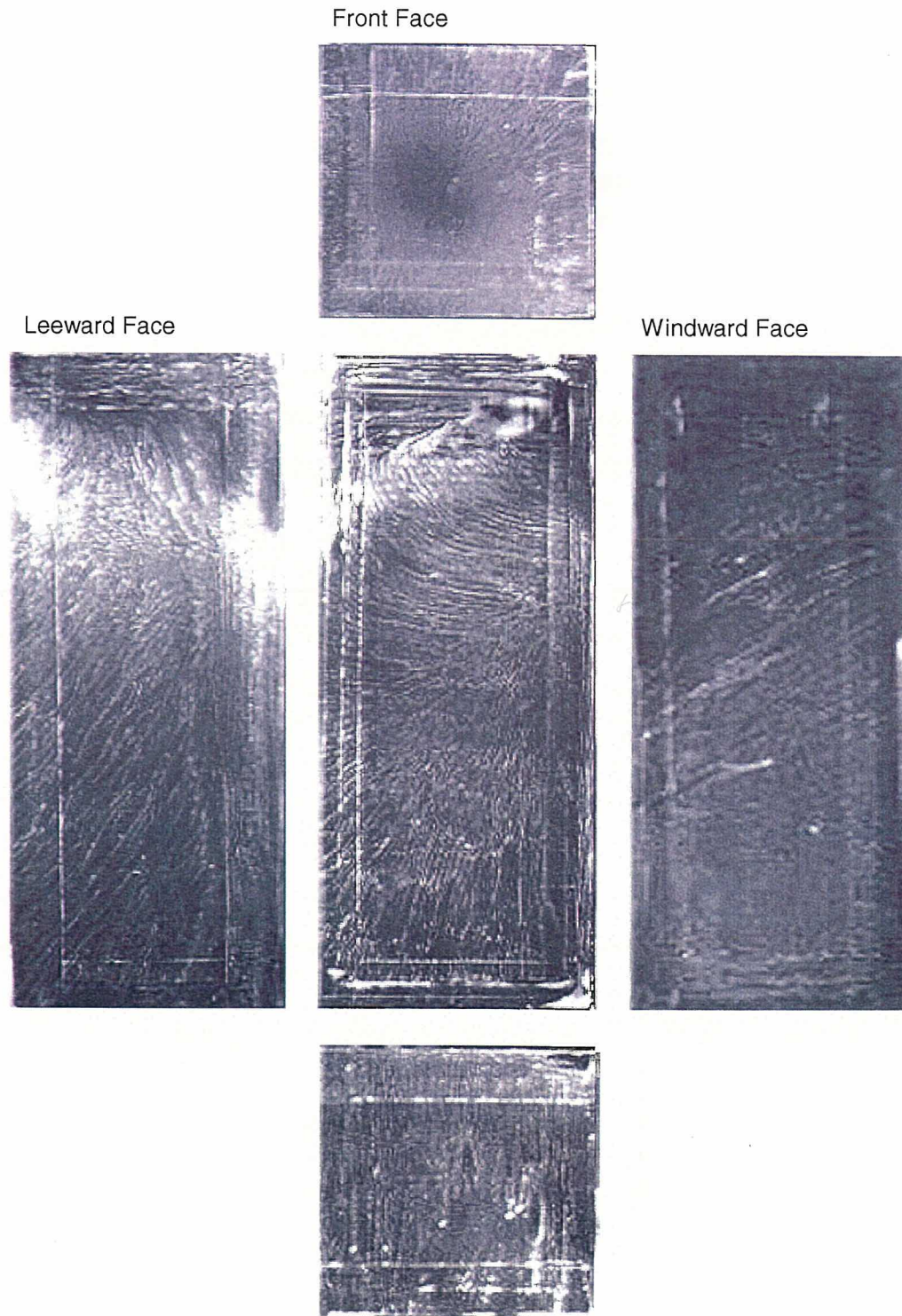


Figure 6-24 Sharp Edged 1-Box Model Surface Paint Flow Visualisation at 10° yaw

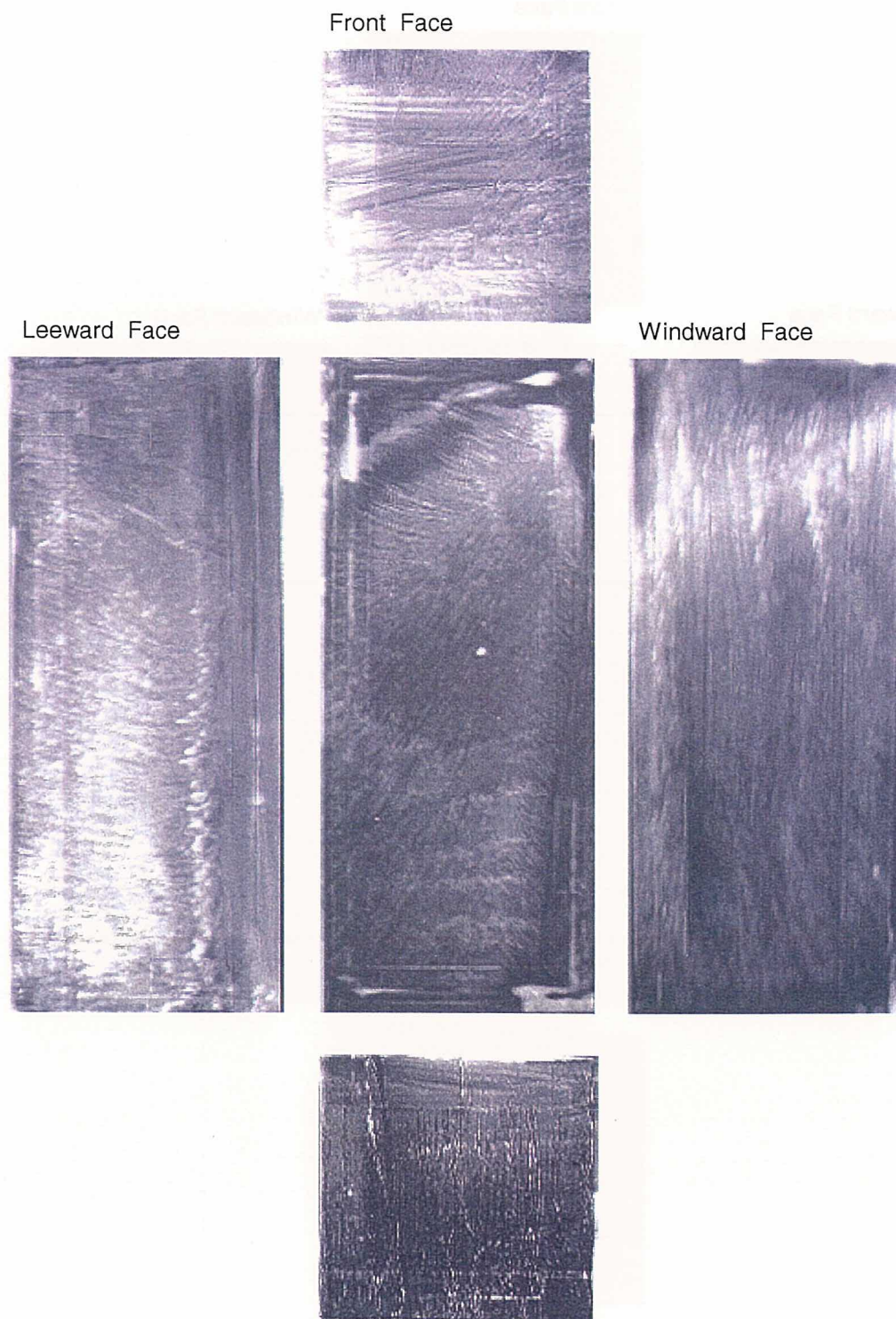


Figure 6-25 Sharp Edged 1-Box Model Surface Paint Flow Visualisation at 20° yaw

Leading Edge to Left of Page

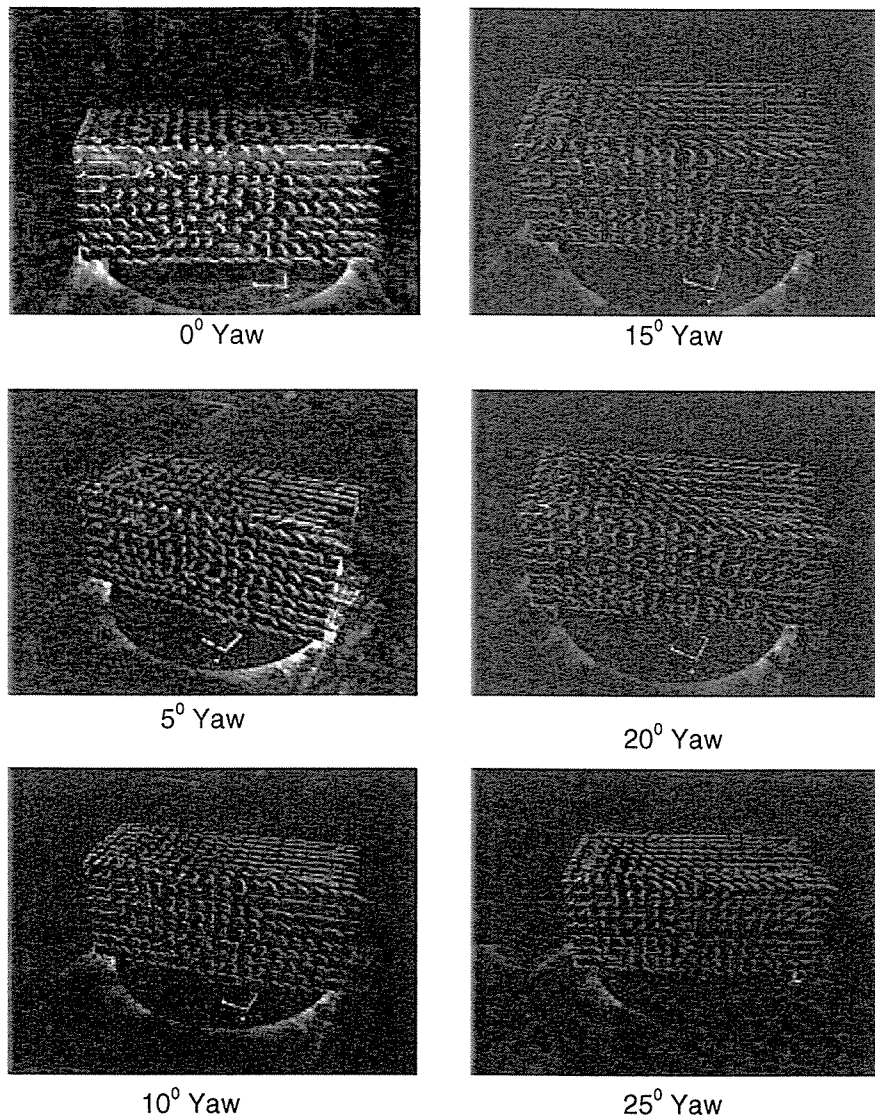


Figure 6-26 Sharp Edged 1-Box Model Flow Visualisation by Fluorescent Tuft 0 - 25° yaw

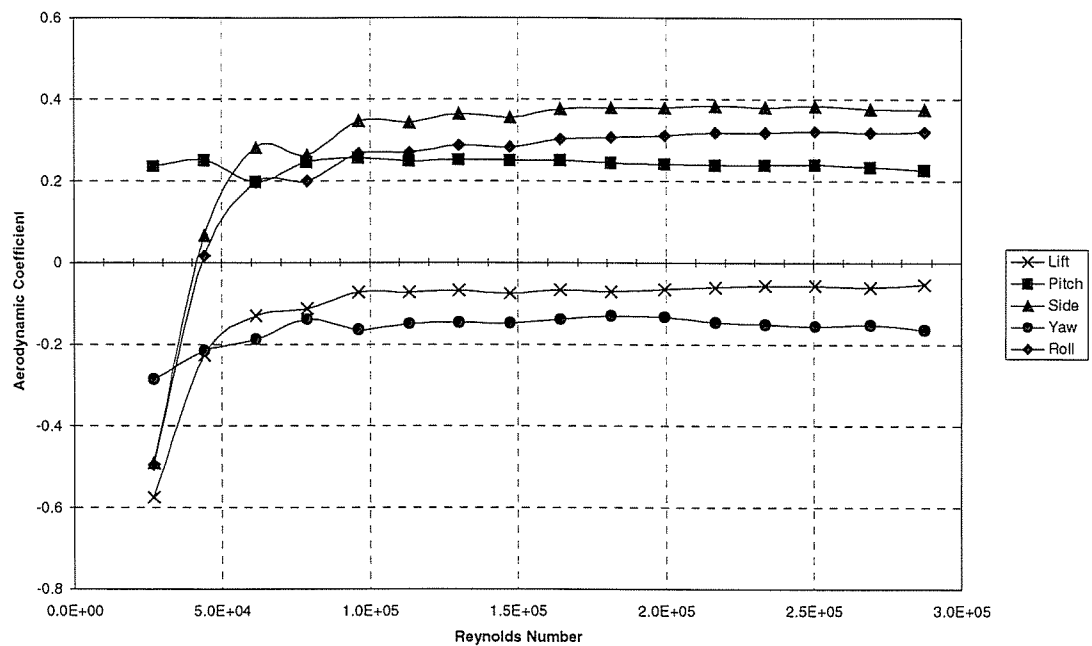


Figure 6-27 Reynolds Sensitivity for Sharp Edged 1-Box Model at 5° Yaw Angle

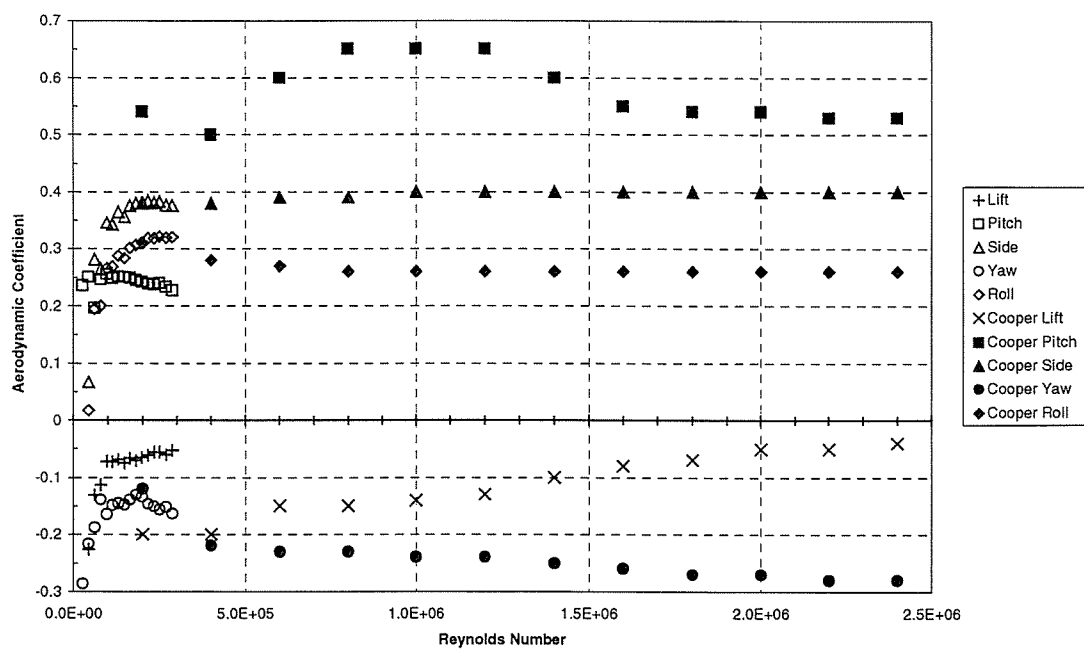


Figure 6-28 Comparison of Reynolds Sensitivity for Sharp Edged 1-Box Model

7. Crosswind Aerodynamics of a Radiused Edged 1-Box Model

7.1 Introduction

Having determined the flow characteristics of the sharp edged 1-box model, the next stage was to determine what effect radiusing of the box edges had upon the flow field. The results of this series of tests show that all steady state aerodynamic force and moment coefficients for a radiused edged 1-box model, with the exception of yawing moment, are approximately the same as the sharp edged case. Comparing coefficient versus yaw angle data for the radiused and sharp edged boxes, it can be seen that the yawing moment coefficient is no longer negative at lower values of yaw. Overall, the steady state yawing moment coefficient for the radiused edged box is greater than the sharp edged box, but the magnitude of the transient peak on entering the crosswind gust is approximately the same.

Transient pressure animations of the radiused edged 1-box model are very similar to the sharp edged case but the leeward separation bubble collapse, previously identified in the sharp edged 1-box model tests appear to be more distinct. This is in part due to overall higher steady state yawing moments for the radiused edged case.

For all steady state tests detailed in this chapter the test speed was 13m/s and for dynamic tests the track speed was approximately 13m/s and the tunnel speed varied to give 5° yaw angle increments $0-25^\circ$. Otherwise, the model arrangement is that described in chapter 4.

7.2 Results

7.2.1 Force Data

7.2.1.1 Steady State Tests

Figure 7-1 to Figure 7-5 show mean values of the aerodynamic force and moment coefficients from zero to 25° in 5° increments and compared with data from Carr⁶⁷. Considering the lift force coefficient first, it can be seen that there are differences between the present study and Carr in both magnitude as well as the trend of the data. Carr recorded no change in the lift force coefficient with increasing yaw angle up to 5° . The lift force coefficient then showed a decrease up to 10° yaw angle and then an approximately linear variation with yaw angle up to value of 0.58 at 25° . Present lift force data is lower than Carr at 0° yaw and then increases approximately linearly with yaw, however there is close agreement at 25° . A comparison of pitching moment coefficients between Carr and the present data (Figure 7-2) show similar trends in both sets of data but the coefficients of the present study are greater, though less so with increasing yaw angle. The relationship of side force coefficient and yaw angle is linear for the present data whereas Carr's data shows an increased response between 10

and 15° and consequent disparity of values at higher yaw angles. Yawing moment coefficients of Carr are greater than present data but both show a linear relationship up to the yaw angle tested. The trend of the rolling moment coefficient versus yaw is that described for side force. For the side force, rolling moment and yawing moment coefficients, the data of Carr is approximately 20% greater at 25° yaw.

7.2.1.2 Dynamic Tests

Figure 7-6 to Figure 7-9 show the aerodynamic force and moment coefficient dynamic traces for nominally $5 - 25^\circ$ yaw angle. Lift force values all show a delayed response on entering the gust and reach an initial peak at about 2.5 body lengths ($x/W = 0.5$) after the nose of the model has entered the gust. There is then a trough in the signatures before the value of the lift force coefficient again increases up until exiting the gust. Pitching moment dynamic traces are impossible to interpret due to excessive oscillations in the signal caused when firing the model. Unfortunately the aerodynamic signal is of the same frequency as the unwanted noise and any further filtering would lose the aerodynamic signal.

The side force response is well defined and shows a rise in entering the gust to the peak value within 1.5 body lengths ($x/W = 0.3$) and slight unsteadiness in the signal thereafter. Transient peaks in the side force dynamic traces on entering the gust are significant at approximately 25° yaw angle where the value at 1.5 body lengths is 10% higher than the averaged value and there is also a small peak on entering at approximately 20° yaw.

Response of the yawing moment coefficients is well defined for all yaw angles. A peak in the signal of approximately 60% higher than the averaged value occurs at 1 body length ($x/W = 0.2$) into the gust. There is oscillation in the signal thereafter and a slight peak on exiting. The yawing moment reaches a minimum at 1 body length ($x/W = 1.2$) after exiting but unlike the sharp edged case, the minimum peaks are all dependent on yaw angle. Rolling moment dynamic traces follow the same trends as that described for side force.

7.2.2 Pressure Data

7.2.2.1 Steady State

Steady state surface pressure coefficient contours for nominally $0 - 25^\circ$ yaw angle in 5° increments are shown in Figure 7-10 to Figure 7-15. The 0° pressure contour map is slightly eccentric to the stated yaw angle. The flow field on the bottom face is characterised by the development of the separation bubble at the leading edge that is skewed with increasing yaw angle so that a negative pressure region develops along the leeward/bottom interface. Above 10° , there is another negative pressure region present at the trailing edge of the bottom face that intensifies as the yaw angle increases.

Leeward face pressure contour maps are initially characterised by the growth of the separation bubble at the leading edge up to 10° yaw. Here the development of another negative pressure region at the leeward/top interface is noticeable.

This is due to the development of a vortex caused by flow accelerating over the top edge. Both regions of negative pressure grow steadily with yaw. As for the bottom face there is also a region of negative pressure at the trailing edge.

The top face shows the separation bubble at the front of the face that is skewed with increasing yaw angle. Negative pressure then grows initially along the leeward interface and then the windward interface. A region of strong negative pressure is evident at the rear windward quarter of the top face above 20° . This region is due to vortex formation from flow accelerating over the windward edge. In addition, at approximately this angle, the regions of negative pressure connect and the entire top face is subject to an overall increased negative pressure by 25° yaw angle.

Windward face pressure contour patterns are dominated by the decrease in separation bubble at the leading edge with increasing yaw angle. By 20° the separation bubble has disappeared and is coincident with the development of a longitudinal region of negative pressure at the top/windward interface. Changes in pressure on the front and rear faces are less dramatic. The stagnation point on the front face moves towards the windward face with increasing yaw angle and the rear face shows the development of a region of negative pressure at the bottom/leeward corner. The average base pressure coefficient on the rear face changes from -0.3 at 0° yaw to -0.6 at 25° yaw.

Calculated changes with yaw angle of aerodynamic force and moment coefficients from integration of steady state pressure contour maps are shown in Figure 7-1 to Figure 7-5. Integrated lift force and pitching moment data is greater than the measured values though the trend of the data is the same. Side force and rolling moments show a good comparison and yawing moment is slightly lower. The differences between calculated forces and moments are in part due to inaccurate computation at the radii of the model. At these edge boundaries the measured pressure is taken at the apex of the radius and assumed to act over the perimeter of the radius. In practice, the radius edges will be an area of significant change in pressure coefficients and some error will inevitably be imparted to the integrated forces and moments.

7.2.2.2 Transient Pressure Animation

Transient surface static pressure animations for the windward, bottom and rear faces at approximately 10° and 20° yaw angle are recorded in 'rboxwbr10.mpeg' and 'rboxwbr20.mpeg' respectively. For both yaw angles, the windward face animation shows a gradual change of the leading edge separation bubble at both gust entrance and exit. There is no collapse of the separation bubble as was previously seen for the sharp edged 1-box model. The bottom face has little transient activity, the leading edge separation bubble is skewed towards the leeward face on entrance to the gust and similarly returns to the zero yaw condition at the gust exit. Stagnation and high negative pressure regions due to the mounting strut can also be identified. Of note is the marked increase in pressure on the rear face just before gust exit, most noticeable for the approximately 20° yaw case.

Surface static pressure animations 'rboxlft10.mpeg' and 'rboxlft20.mpeg' show transient pressures of the leeward, front and top faces at approximately 10° and 20° yaw. As the model enters the gust the leeward face separation bubble gradually decreases in strength and length and a longitudinal area of negative pressure develops along the leeward/top face. The separation bubble at the leading edge of the top face is swept toward the rear leeward face and a negative pressure region develops along the top/windward interface. After exiting the gust the leeward edge separation bubble collapses at approximately $0.3x/l$ downwind of the leading edge and to a point located at the top edge. Only after the top face returns to the zero yaw condition and the longitudinal separation along this edge dissipates, does the separation bubble return at the leading edge. The front face animation shows the movement of the stagnation point from windward to leeward before exiting.

Mean pressure contour maps of the transient pressure animations (Figure 7-16 and Figure 7-17) show differences from the steady state contour maps at 10° and 20° yaw (Figure 7-12 and Figure 7-14). The bottom face shows a region of negative pressure immediately behind the strut and a well-defined region of positive pressure in front of the strut not evident in the steady state tests. The form of the leading edge separation bubble is also different. The mean pressure coefficient in the leeward face leading edge separation bubble is not as strong for the mean dynamic case and the trailing edge negative pressure region has not developed by 20° . Steady state and mean dynamic pressure contour maps of the windward and front faces show a good comparison for both yaw angles. Average base pressure coefficients are -0.25 and -0.4 for 10° and 20° yaw angle respectively, compared with -0.3 and -0.6 for the steady state condition. In general, mean dynamic negative pressures are overall greater and show marked differences from the steady state in the rear half of the pressure contour maps. This is indicative of the steady state flow field not being established during dynamic tests.

Integration of pressures to give force and moment dynamic traces are reproduced in Figure 7-6 to Figure 7-9. For the lift force coefficient there is a good comparison at 10° yaw and also at 20° where the integrated pressure signature also identifies the initial peak on entering the gust. Side force and rolling moment show a very good comparison but the integrated yawing moment dynamic trace is greater at 20° yaw angle.

Figure 7-18 shows changes in the yawing moment coefficient on the leeward and windward faces. It can be seen that it is the windward face that contributes the greatest magnitude to the yawing moment but transient responses are more significant on the leeward face. Unlike the sharp edged case, the windward face transient peak at gust entrance is not present.

Changes in force coefficients for the longitudinal faces of the radiused edged model are shown in Figure 7-19. Forces on the bottom and top face do not reach a steady value during the dynamic tests.

The magnitude and location of peak pressures on the leeward face are shown in Figure 7-20 and Figure 7-21. The figures clearly identify a minimum negative

pressure just after the gust exit. The only discernible features are that the minimum negative pressure occurs $\frac{1}{2}$ body length ($x/W = 1.1$) after gust exit and at approximately $0.52 x/l$ from the trailing edge. This is coincident with the position of leeward vortex collapse identified from transient pressure animations.

7.2.3 Flow Visualisation

Flow visualisation by the application of surface paint at 0° yaw is shown in Figure 7-22. The position of the reattachment point on the top face is identifiable at approximately $0.9 x/l$ from the leading edge. The leeward face shows a region of circulating flow at the leading bottom corner and then flow is directed towards the midpoint of the top edge. Attached flow of the leeward face can be seen between this point and the trailing edge bottom corner. With increasing yaw (Figure 7-23 and Figure 7-24), skewing of the leading edge reattachment point on the top face can be seen and the general attached flow is parallel to the direction of the free stream and from the windward leading to leeward trailing edge. By 20° , the stagnated region originating from flow accelerating over the top/windward face and reattaching is identifiable. The leeward face at 10° shows the movement of separation bubble reattachment towards the trailing edge and the development of a second reattachment point originating from the top face.

Stills taken from flow visualisation of the radiused box model by fluorescent tuft are in agreement with the surface paint tests. Figure 7-25 shows stills taken from flow visualisation of the top and leeward faces by fluorescent tufts from $0 - 25^\circ$. On the leeward face the general pattern of fluid flow is that previously described for the surface paint tests. Flow is directed from the leading edge corners towards the centre of the leeward face and longitudinal vortices develop along the upper and lower edge with increasing yaw angle. Vortices present on the top face at the leading edge and windward interface can also be identified.

7.3 Discussion

7.3.1 Previous Work

Carr⁶⁷ provides the most useful data to be used for a direct comparison here. He found that the yawing moment coefficient showed an increase with increasing edge radius whilst side force, rolling and pitching moment coefficients all showed reductions. The following points are of interest:

- Yawing moment was most sensitive to radius changes up to $r/h = 0.033$, above this value the yawing moment changes little (where r/h is the edge radius normalised by body height)
- The greatest change in side force occurred for edge radius changes from $r/h = 0.1$ to $r/h = 0.2$
- The lift force coefficient showed an initial increase at $r/h = 0.033$ but then a decrease up to $r/h = 0.1$ where there is a rapid change up to $r/h = 0.2$. At r/h

= 0.2 and 0.3, lift coefficients are almost independent on increase in yaw angle.

Pressure measurements by Carr⁶⁷ showed that the size and minimum pressures within separation bubbles generated at the leading edges were all reduced with increased normalised radii. Surface static pressure contour maps by Carr also showed that an increase in edge radius broke down the longitudinal vortex present along the leeward/top interface and the longitudinal vortex and leading edge separation bubble on the top face. These changes in pressure are coincident with increases in yawing moment and decreases in lift force with increasing yaw angle. It can then be assumed from Carr's results and the work presented here that the magnitude of the yawing moment is influenced by the longitudinal vortex at the leeward/top interface and similarly, the lift force is influenced by the longitudinal vortex at the top/windward interface. Moreover, it is the formation and collapse of these vortices which is most evident in the transient pressure animations and therefore can be assumed to influence the peaks in yawing moment. This is also evident in the present research and is shown in Figure 7-8. It is apparent from the data of Carr and the present research that the changes in aerodynamic force and moment coefficients are sensitive to changes in edge radius. The manufacture of the models will contain errors and combined with differences in wind tunnel turbulence modeling and differing Reynolds numbers, it is not surprising then that there are discrepancies between Carr and present data (Figure 7-1 to Figure 7-5).

Reynolds number sensitivity around radiused edged bodies is increased over sharp edged bodies since the fluid contact surface is greater and hence the viscous force of the fluid is greater. Figure 7-26 shows Reynolds number sensitivity tests for the radiused box model from 2 to 17m/s and at 5° yaw angle. Variation of the aerodynamic coefficients is similar to that for the sharp edged box model (Figure 6-27) and it can be concluded that the radiused edged model is insensitive to changes in Reynolds number in the sub critical regime and at a test speed of 13m/s. On his work on the effect of front edge rounding, Cooper⁶⁸ conducted Reynolds sensitivity tests on box type models up to and through the critical Reynolds number. For a non-dimensional radius of $r/h = 0.1$, it was found that the side force and rolling moment are unaffected by changes in Reynolds number but that pitching and yawing moments vary significantly. This is shown in Figure 7-27 which compares Reynolds number sensitivity test of Cooper and the present data of the radiused box model at 5° yaw angle. As previously explained for the sharp edged model (section 6.3.1), the figure demonstrates that the radiused edged test data cannot be extrapolated to full scale.

In terms of actual measurement made in crosswind conditions, Kobayashi¹⁴ provides the closest comparison with test data on a 1-box type vehicle in a crosswind generator. It was found that the peak yawing moment occurs at 1.4 body lengths into the gust and a steady state is achieved by 8 body lengths. This result was also confirmed in moving scale model tests, though the magnitude of the peak on gust entrance was greater. Unfortunately it is not possible to compare force and moment values of Kobayashi and the present work because it is uncertain how the coefficients are calculated. Kobayashi also

took pressure measurements on a line along the leeward face and recorded similar trends to those presented here. From the pressure measurements it was concluded that the peak in yawing moment on gust entrance is caused mainly by a change in flow structure on the leeward face and the generation of large negative pressures. On investigations into the effects of radiusing of the front edges, Kobayashi found that increased radius caused a decrease on the peak yawing moment response but increase in the steady state response. Pressure distributions confirmed that the mechanisms of this change were due to increased overall leeward face pressures, but that the area of peak pressure is much smaller in the radiused case hence lower peak yawing moment. It is also unfortunate that Kobayashi did not present data after the gust exit and which could be correlated with the presence of the exit yawing moment peak that is so noticeable in the present research.

The experimental work of Kobayashi has also been used as the basis of comparison for a computational model⁴⁸. In addition to examination of the yawing moment coefficient, the computational model allowed examination of the other coefficients. An encouraging result recorded in the research was that the variation of lift force displays very similar trend to that observed here, namely a peak on entrance followed by a trough (occurring at 3.5 body lengths) and a second peak before the gust exit.

Takada⁸ has also conducted full-scale transient tests on 1-box type vehicles. Of interest to the current research, it is noted that the peak leeward negative pressures on gust entrance are replicated and also the maximum and minimum peak yawing moments at the gust entrance and exit. This has significant implications for the test method used in the present research. Initially it was uncertain if the minimum peak on gust exit is caused by outflow or blockage effect as the model passes through the opening of the wind tunnel working section. The correlation with the work of Takada (where measurements were taken during runs past a crosswind generator) suggests this not to be the case and that it is an aerodynamic effect. Further correlation between full-scale and the present research is observed in the side force and rolling moment dynamic traces which are both seen to increase up to exiting the gust (a distance of approximately 5 body lengths).

Dominy³³ used the secondary gust source technique to simulate the transient gust and has collected data on models similar to that tested here. The quasi-2D model used was of similar aspect ratio and with approximately equal non-dimensional radii ($r/h = 0.11$) but tests were conducted at a different Reynolds number. Tests of Dominy were performed at a Reynolds number based on body length of 2×10^5 which differs from the current investigation of 4.7×10^5 at 25° yaw. As mentioned previously the change in Reynolds number is critical in determining flow characteristics and a quantitative comparison is not possible. Nevertheless, the data collected by Dominy serves as a useful comparison between the two scale-model transient test techniques. At zero yaw angle the axial surface static pressure distribution around the Dominy model has many similarities with that recorded in the present research. Flow separates at the leeward leading edge to form a separation bubble and there are also pressure

changes occurring at the trailing edge. Pressure data presented with the model in the gust at a relative angle of 30° are difficult to interpret because it is unclear how pressure coefficients are calculated and pressures greater than unity are presented. However, the data still displays the general trend of flow structure on the side faces; the growth of the stagnation point towards the windward leading edge and development of the leeward separation bubble. Of the limited amount of data that is presented, none reveals any increased transient characteristics such as position and magnitude of peak pressure changes.

The surface pressure of the 2-dimensional Docton model has also been investigated by Sims-Williams⁶⁰ during steady state flow conditions. A comparison of the secondary gust source technique and steady state conditions is therefore possible but only for 0° yaw angle. The work shows that dynamic conditions underestimate the leeward separation peak pressure and length of the separation bubble from the leading edge.

7.3.2 Comparisons with Sharp Edged 1-Box Model

All steady state aerodynamic force and moment coefficients for the radiused edged 1-box model, with the exception of yawing moment, are approximately the same as the sharp edged case. Comparing coefficient versus yaw angle traces for the radiused and sharp edged boxes, it can be seen that the yawing moment for the radiused case is no longer negative at lower values of yaw. Overall, the mean yawing moment coefficient for the radiused edged box is greater than the sharp edged box, but the magnitude of the transient peak on entering the gust is approximately the same.

Concerning surface static pressure measurements, the effects of radiusing cause the area of longitudinal negative pressure along the upper edge to intensify. It would be expected that this would result in a greater peak yawing moment at the gust exit. In fact the yawing moment is less because the localised high-pressure region has moved towards mid axis of the face with a consequent reduction in peak yawing moment.

The trend of the leeward separation bubble collapse of the radiused edged 1-box model at gust exit is very similar to the sharp edged case. The influence of changes in flow structure on the top face to the separation bubble collapse requires further investigation.

7.4 Conclusions

The conclusions from the radiused 1-box model experiments are:

1. Steady state lift force, side force, yawing moment and rolling moment coefficients all display an approximate linear relationship with increasing yaw up to 25° yaw angle.
2. The transient yawing moment response of the radiused edged box is characterised by maximum and minimum peaks on gust entrance and exit. Gust entrance peaks are approximately 1.5 times greater than the steady state value.

Furthermore, comparisons with the sharp edged case show that:

3. The steady state flow field around a bluff body is changed by radiusing of the leading edge. This provides benefits for all aerodynamic coefficients with the exception of yawing moment.
4. Edge radiusing of a box model has the effect of increasing the steady state yawing moment due to increased localised pressures.
5. In dynamic tests, the peak in yawing moment on gust entrance remains the same as the sharp edged case but the peak at gust exit is reduced because the point of action of the moment has moved towards mid-axis

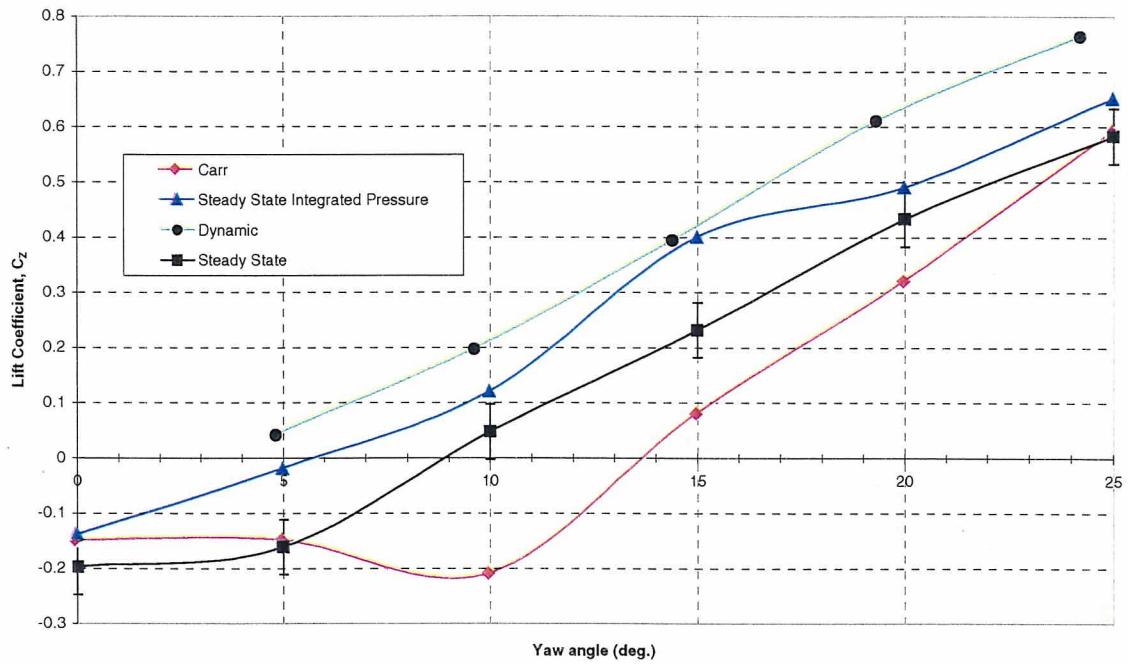


Figure 7-1 Variation of Lift Force Coefficient with Yaw Angle for Radiused Edged 1-Box Model

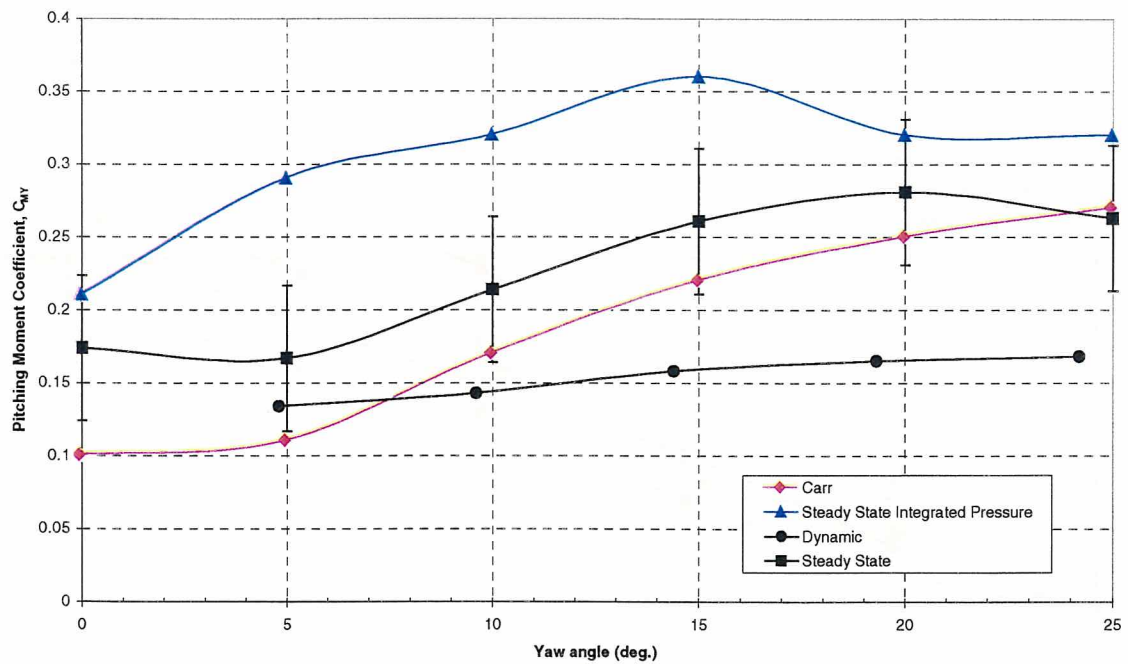


Figure 7-2 Variation of Pitching Moment Coefficient with Yaw Angle for Radiused Edged 1-Box Model

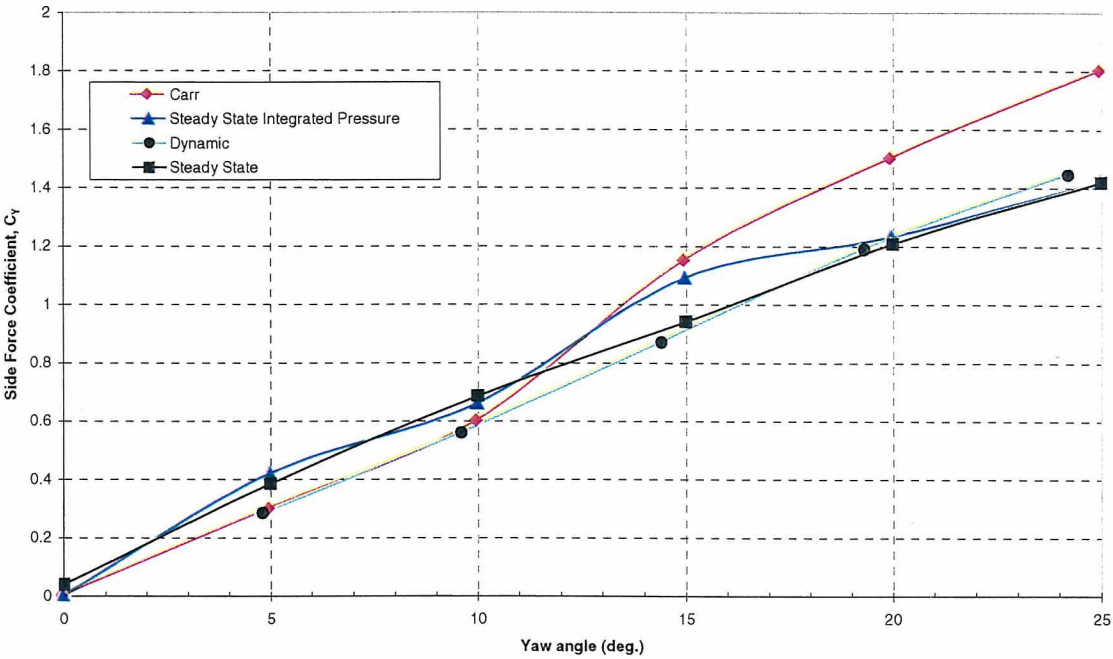


Figure 7-3 Variation of Side Force Coefficient with Yaw Angle for Radiused Edged 1-Box Model

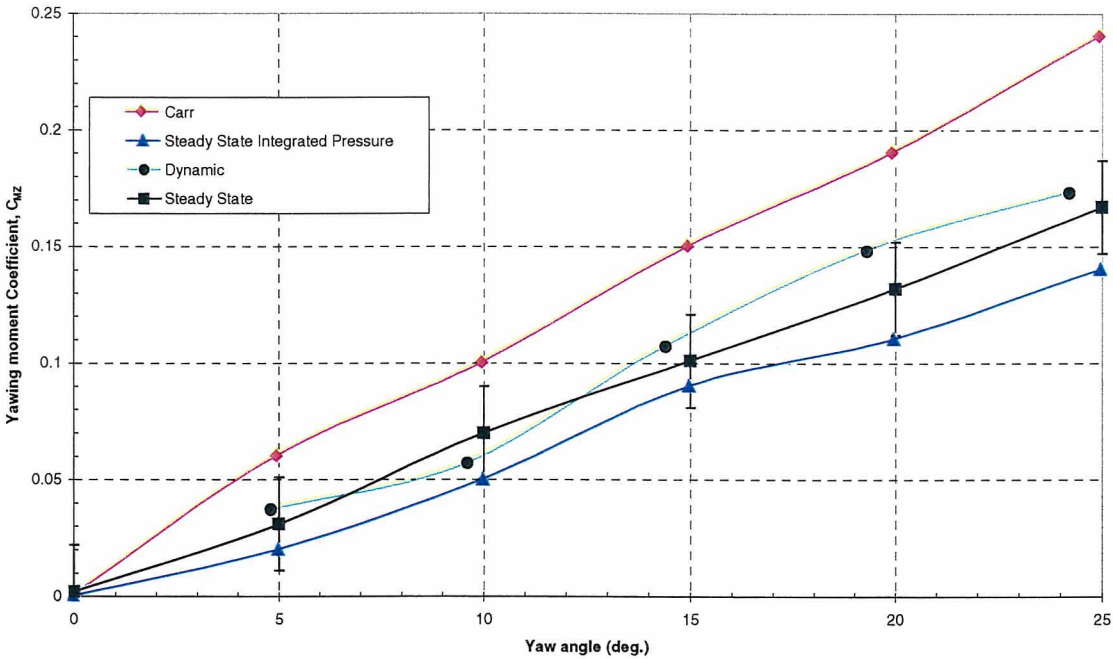


Figure 7-4 Variation of Yawing Moment Coefficient with Yaw Angle for Radiused Edged 1-Box Model

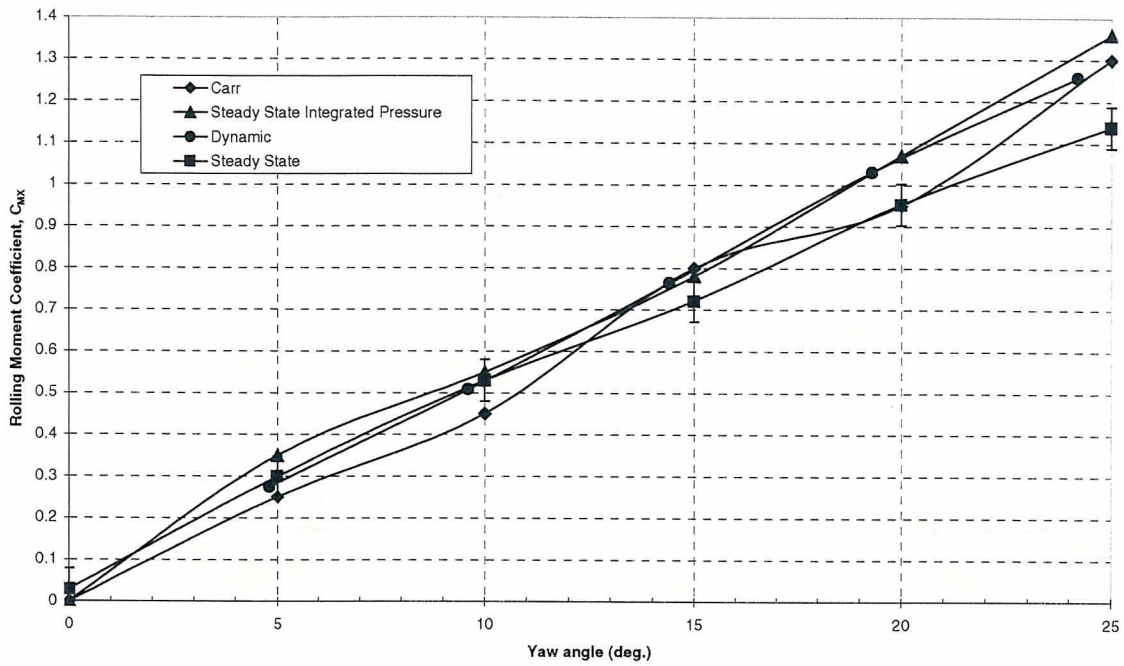


Figure 7-5 Variation of Rolling Moment Coefficient with Yaw Angle for Radiused Edged 1-Box Model

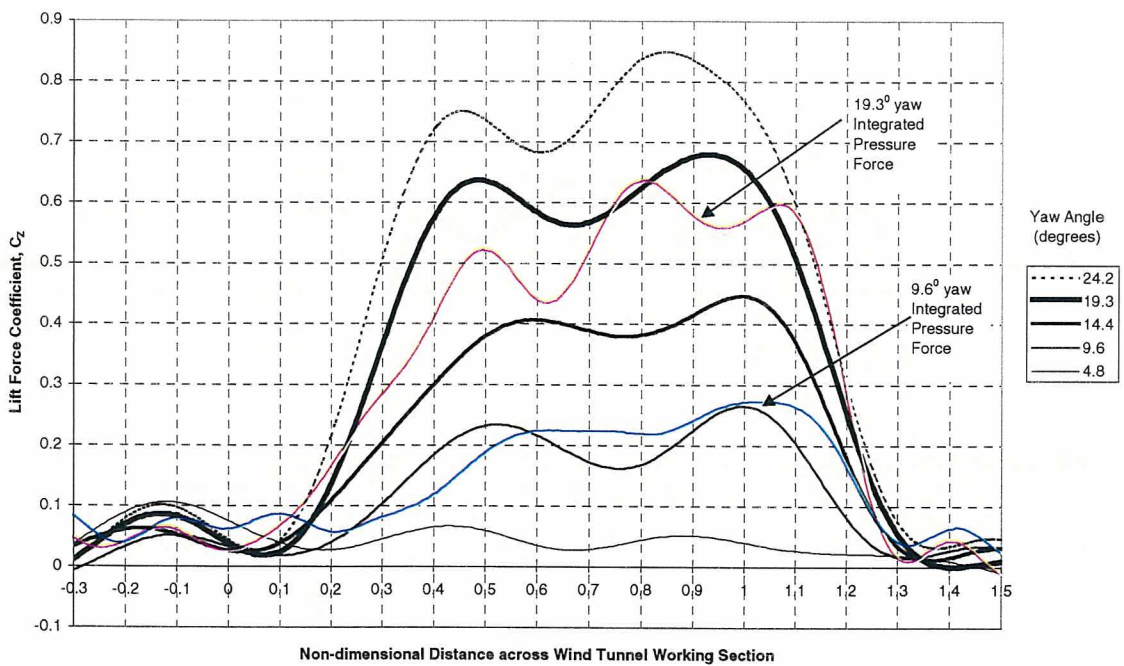


Figure 7-6 Radiused Edged 1-Box Model Lift Force Coefficient Dynamic Traces for 5 - 25° Yaw Angle

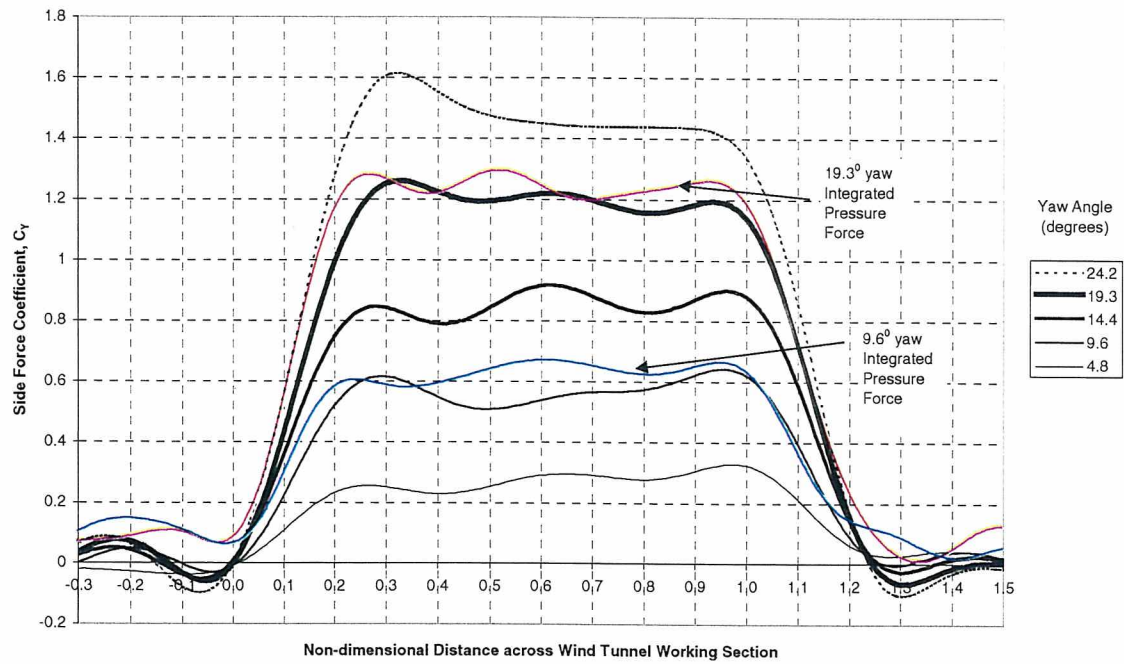


Figure 7-7 Radiused Edged 1-Box Model Side Force Coefficient Dynamic Traces for 5 - 25° Yaw Angle

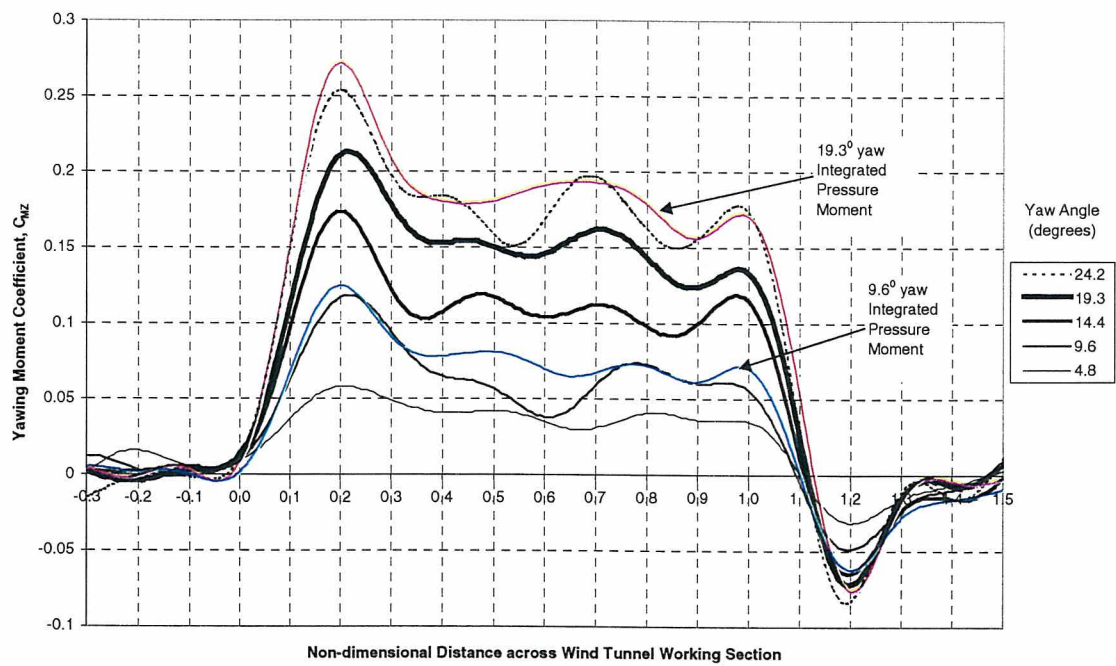


Figure 7-8 Radiused Edged 1-Box Model Yawing Moment Coefficient Dynamic Traces for 5 - 25° Yaw Angle

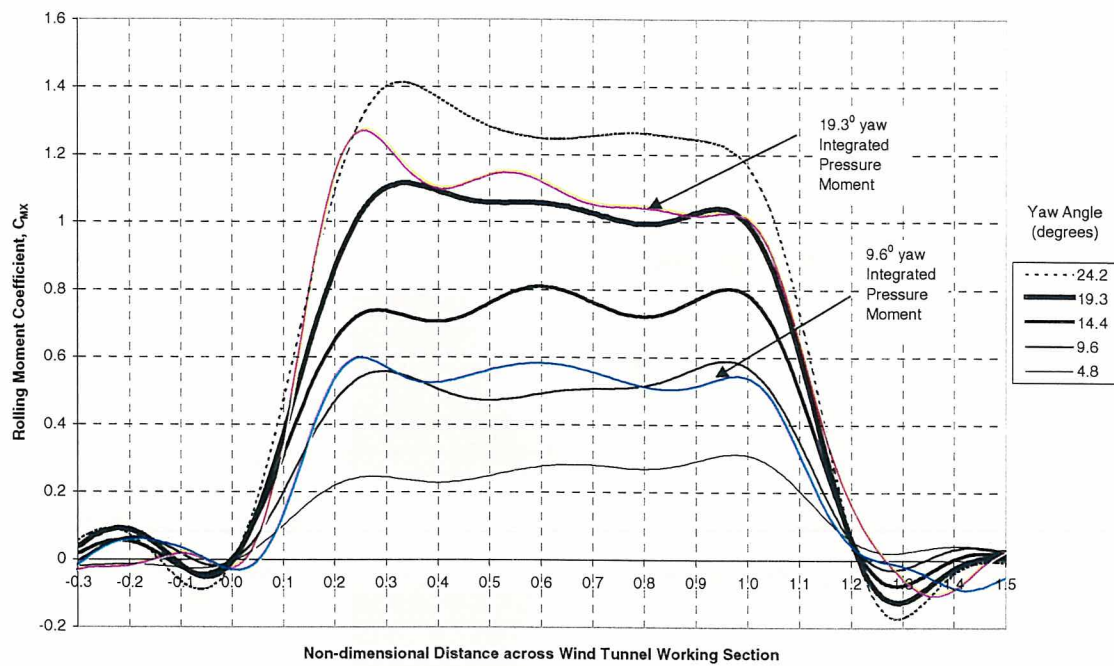


Figure 7-9 Radiused Edged 1-Box Model Rolling Moment Coefficient Dynamic Traces for 5 - 25° Yaw Angle

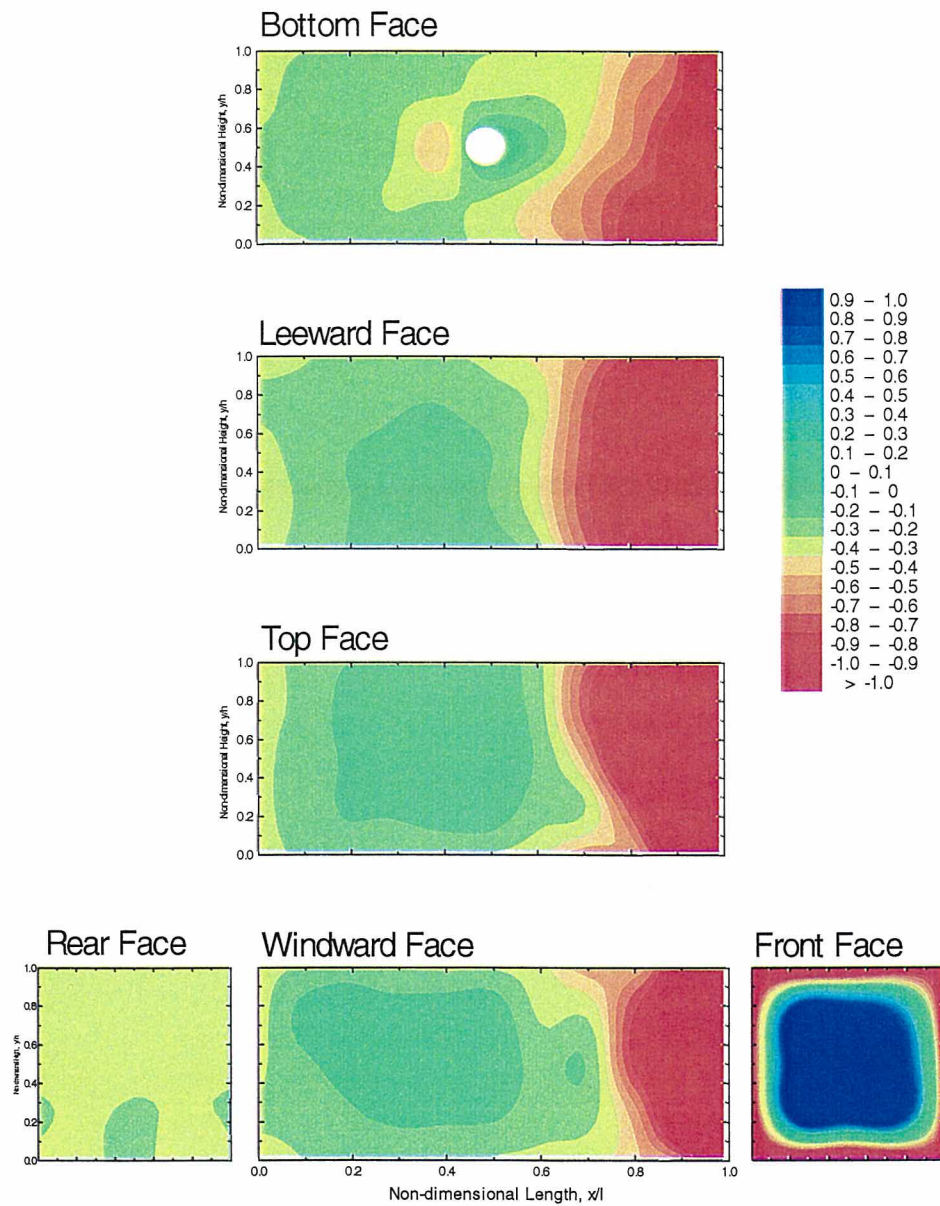


Figure 7-10 Radiused Edged 1-Box Model Steady State Pressure Map at 0° Yaw Angle

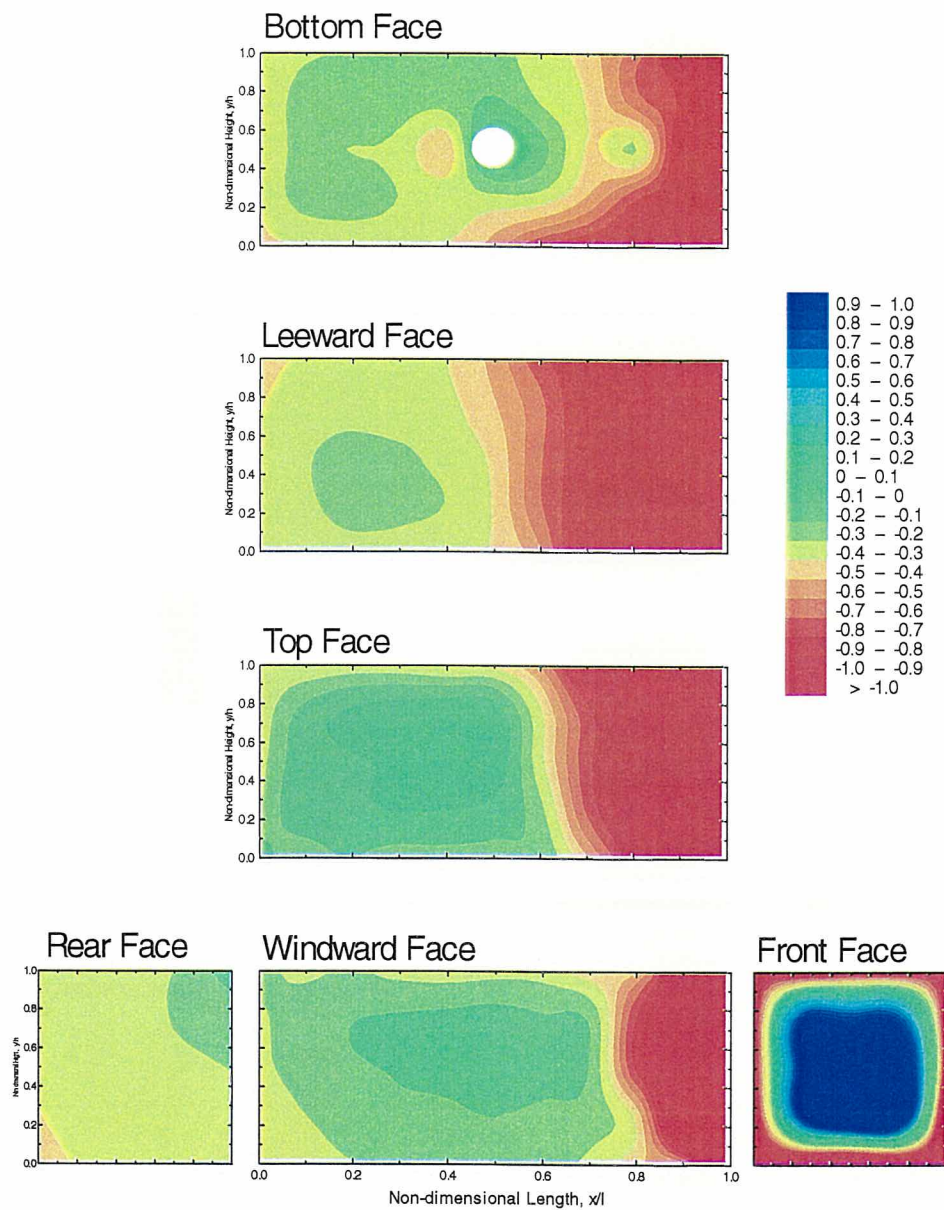


Figure 7-11 Radiused Edged 1-Box Model Steady State Pressure Map at 5° Yaw Angle

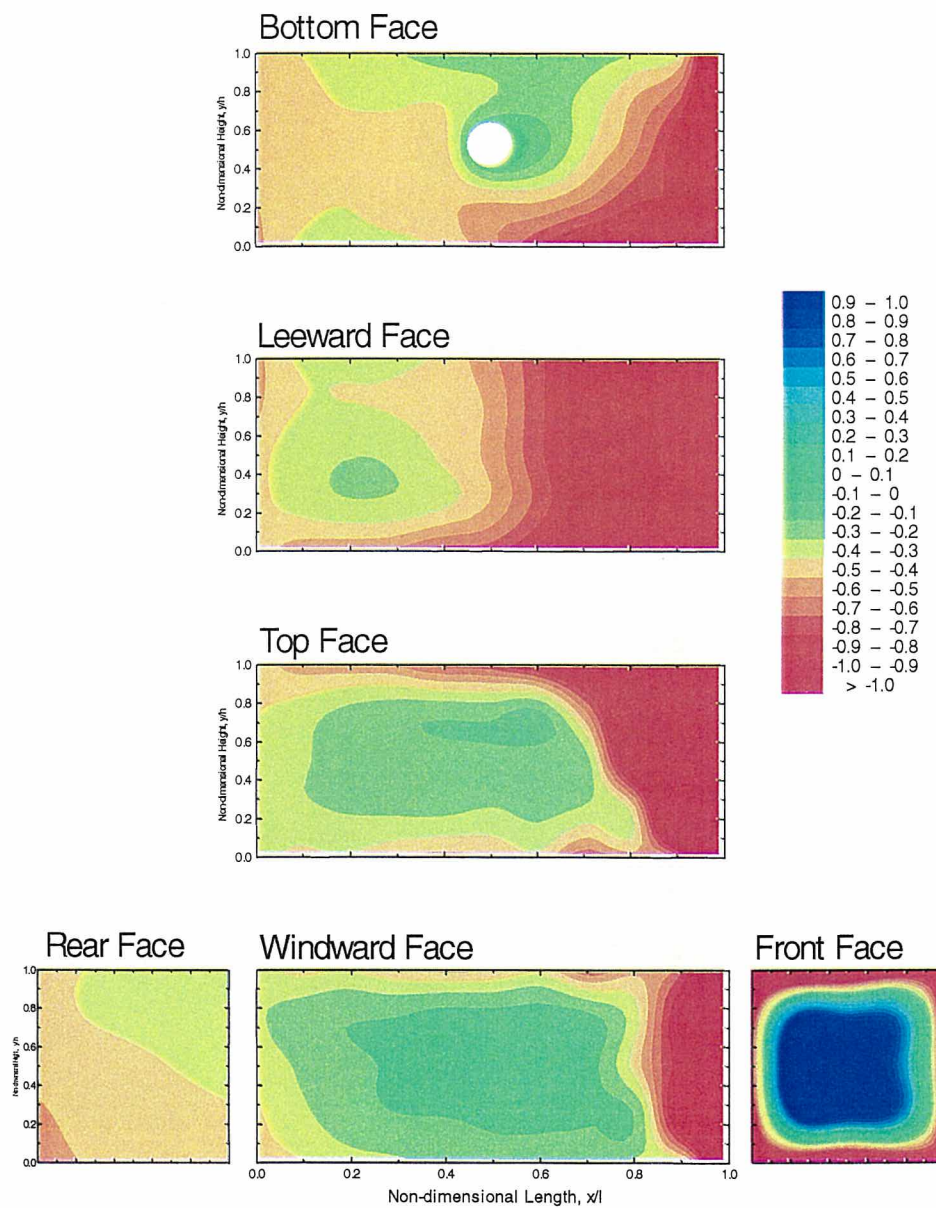


Figure 7-12 Radiused Edged 1-Box Model Steady State Pressure Map at 10° Yaw Angle

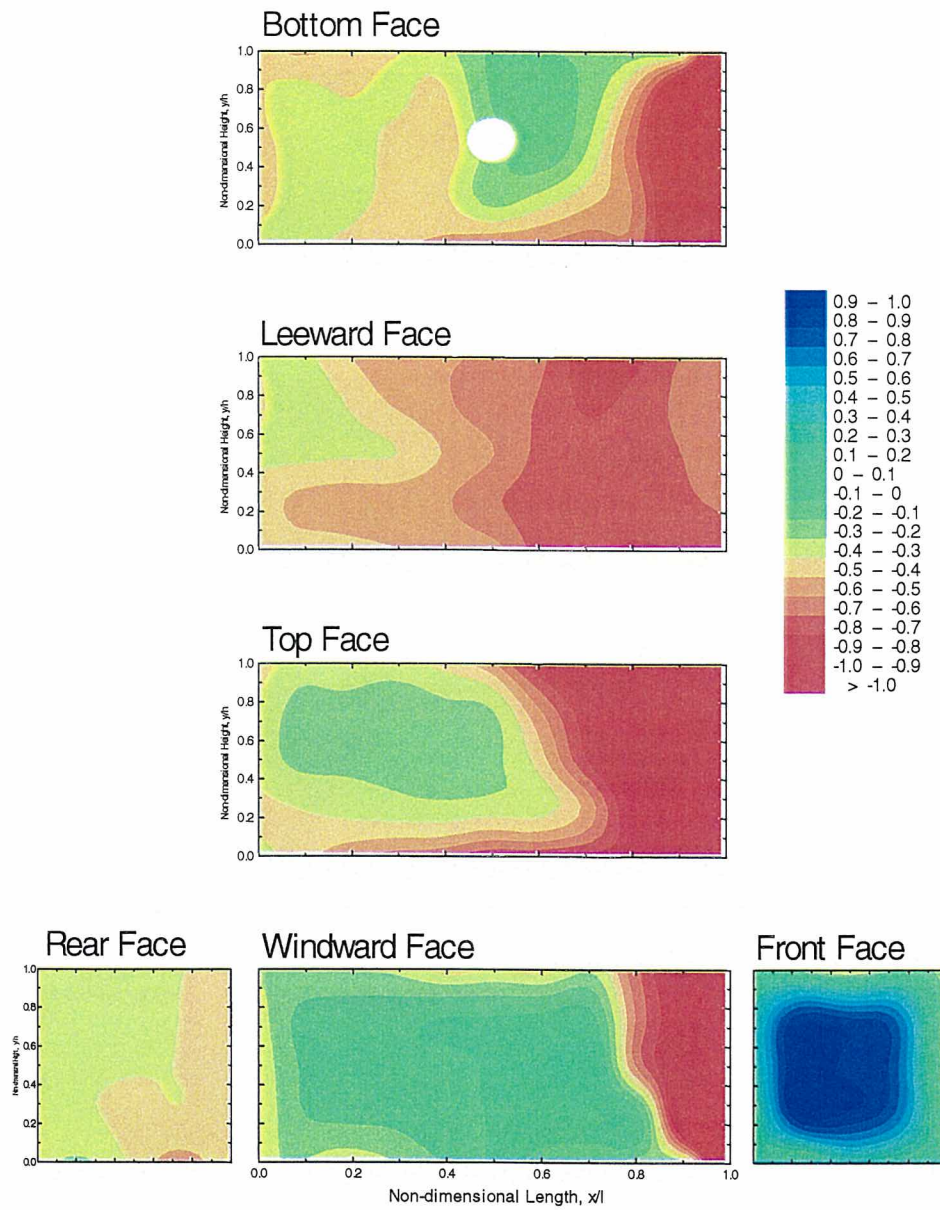


Figure 7-13 Radiused Edged 1-Box Model Steady State Pressure Map at 15° Yaw Angle

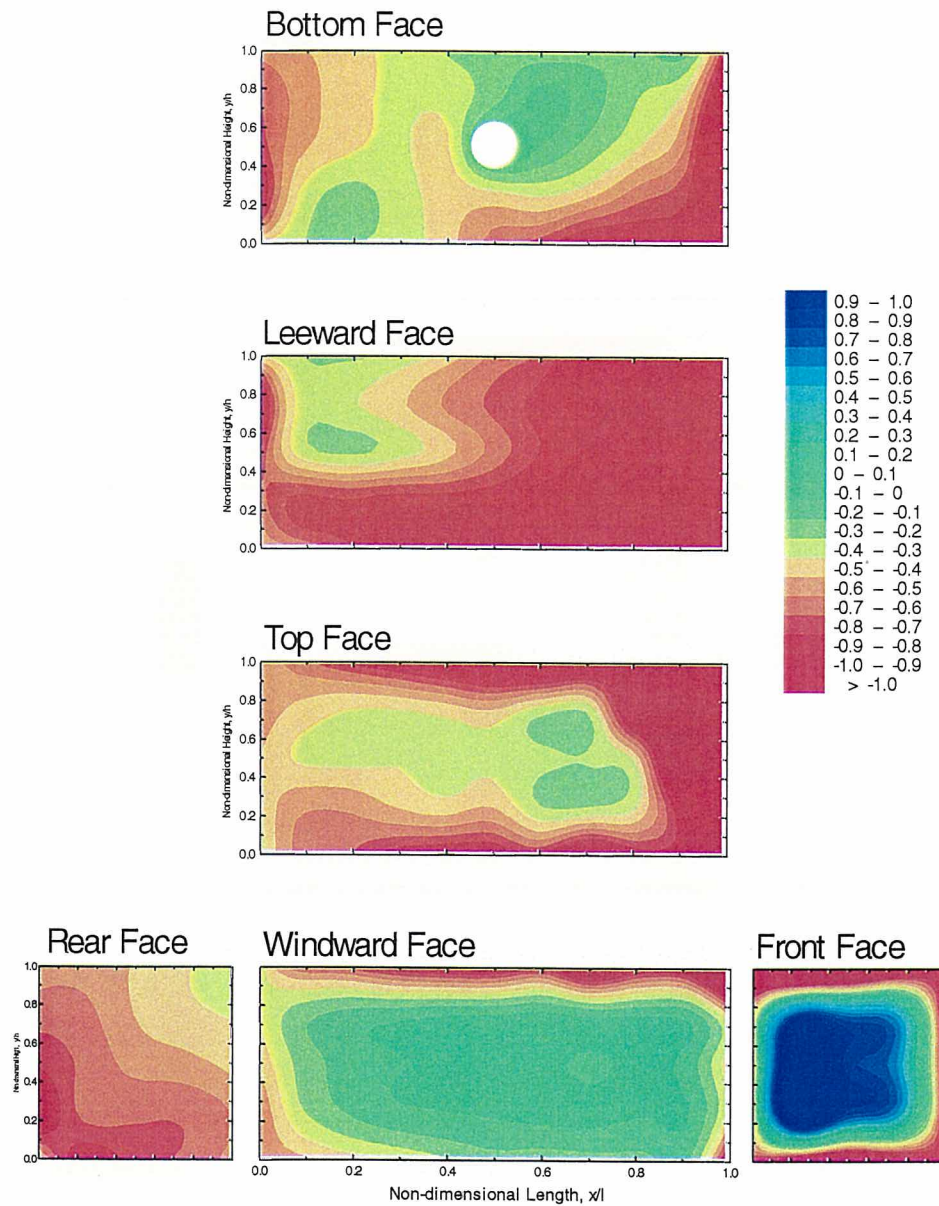


Figure 7-14 Radiused Edged 1-Box Model Steady State Pressure Map at 20° Yaw Angle

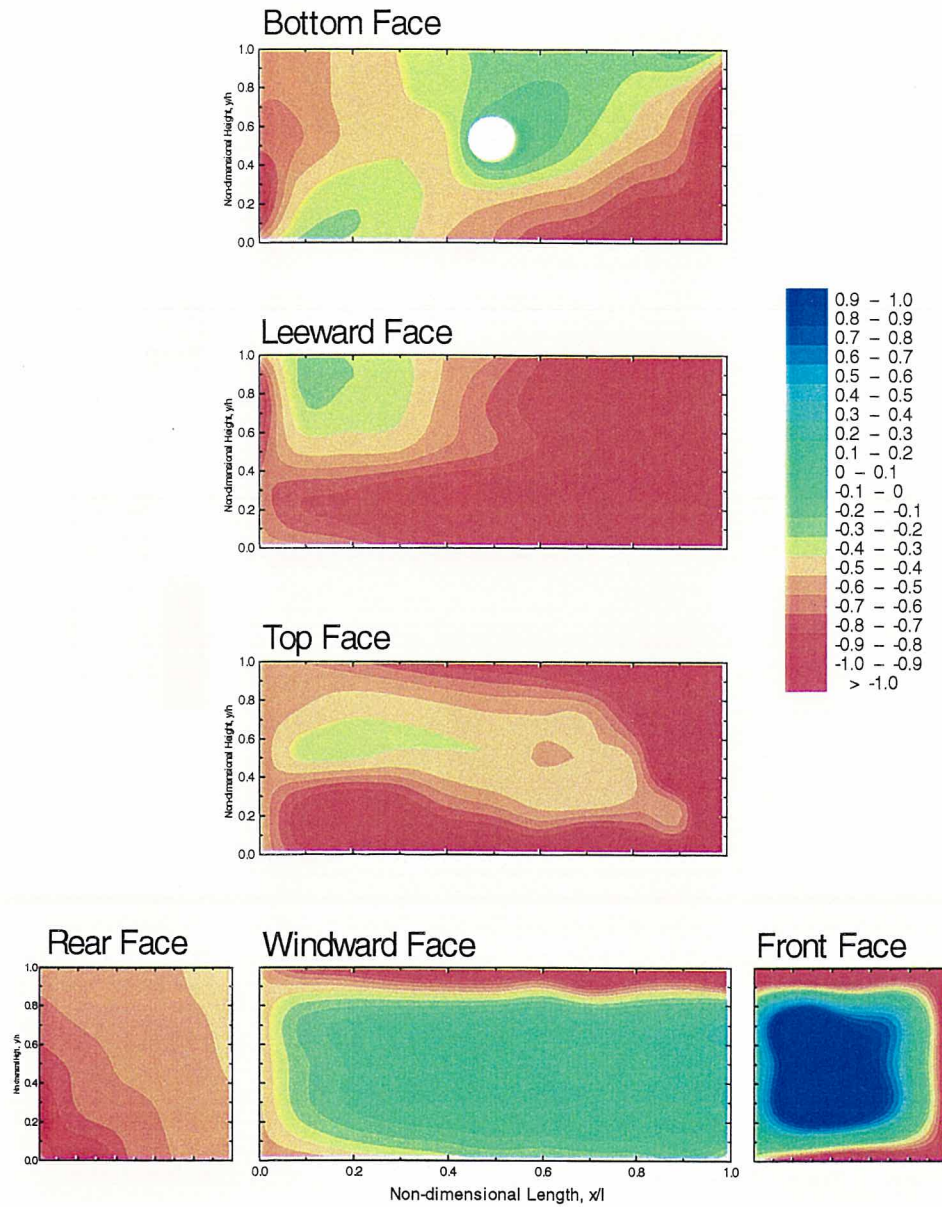


Figure 7-15 Radiused Edged 1-Box Model Steady State Pressure Map at 25° Yaw Angle

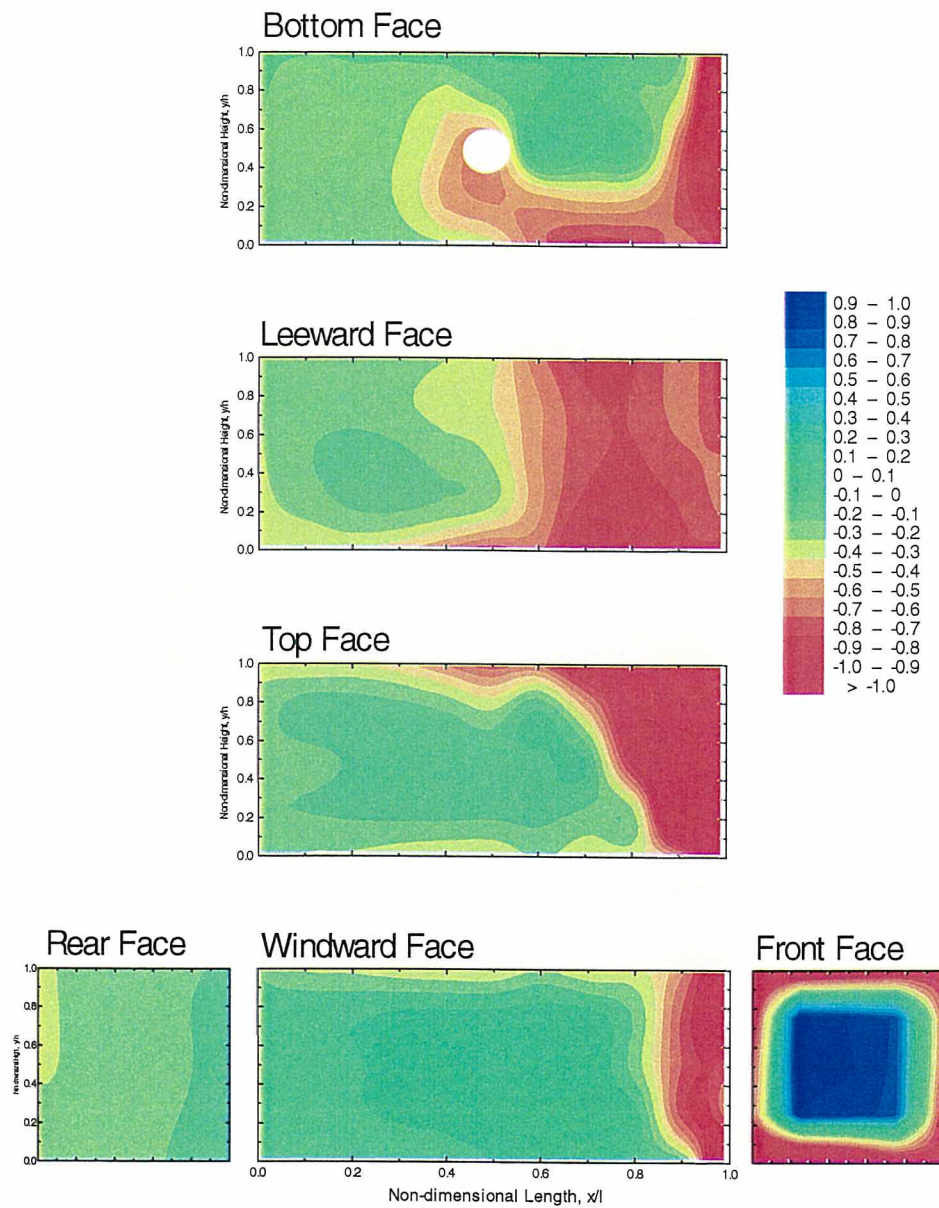


Figure 7-16 Radiused Edged 1-Box Model Mean Dynamic Pressure Map at 10° Yaw Angle

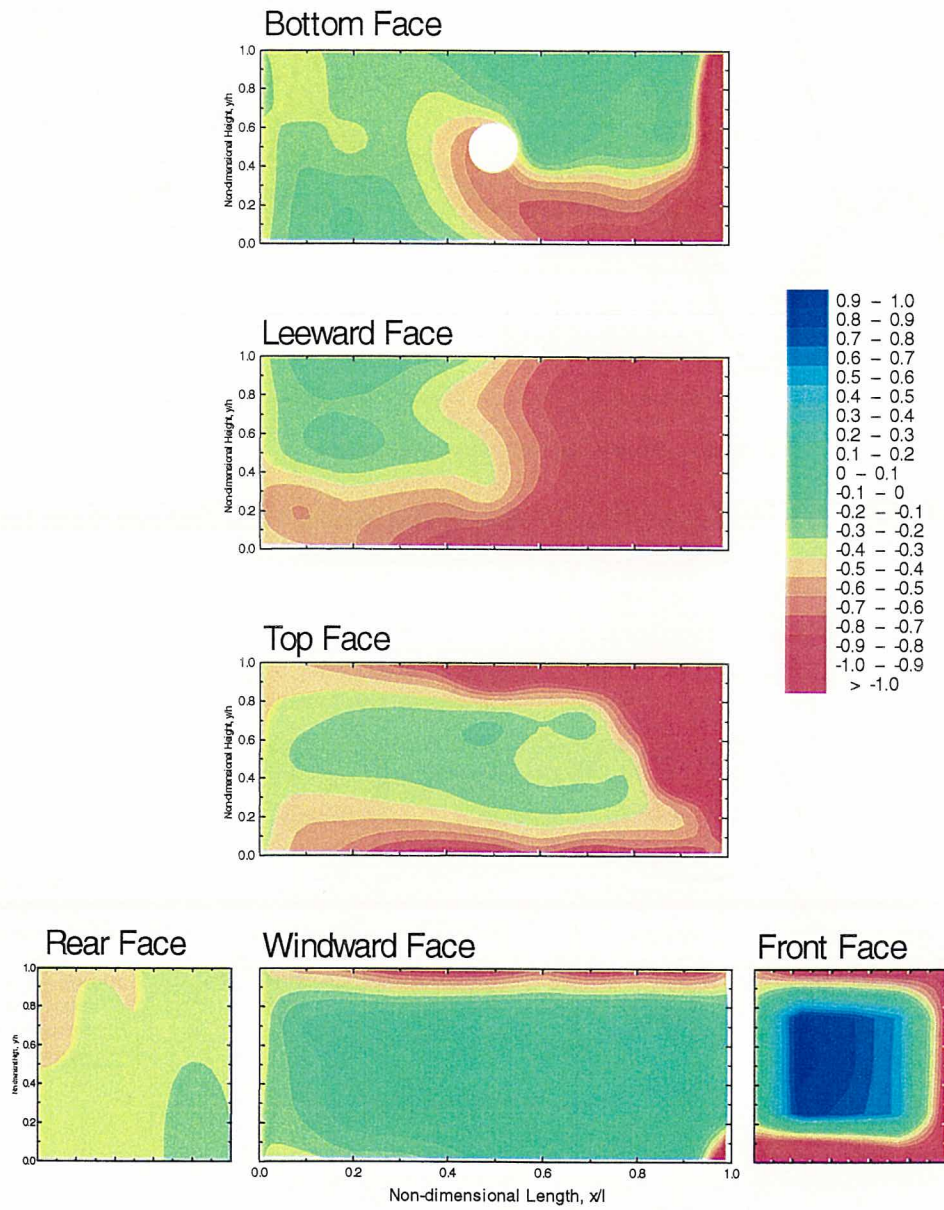


Figure 7-17 Radiused Edged 1-Box Model Mean Dynamic Pressure Map at 20° Yaw Angle

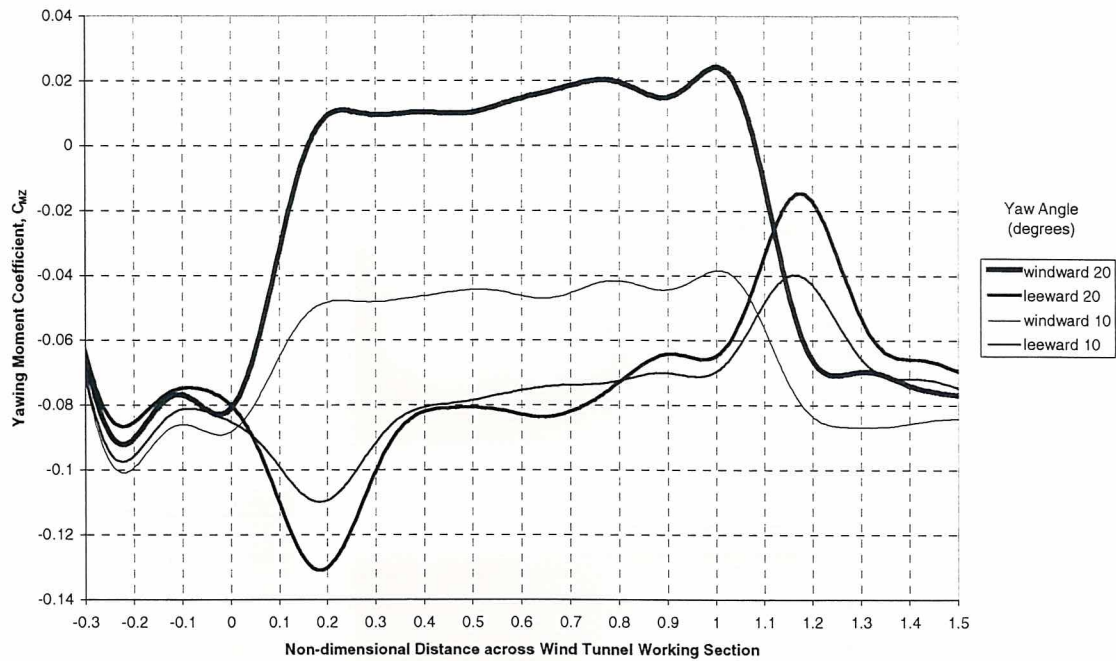


Figure 7-18 Changes in Radiused Edged 1-Box Model Moment Coefficients Calculated from Dynamic Pressure Tests

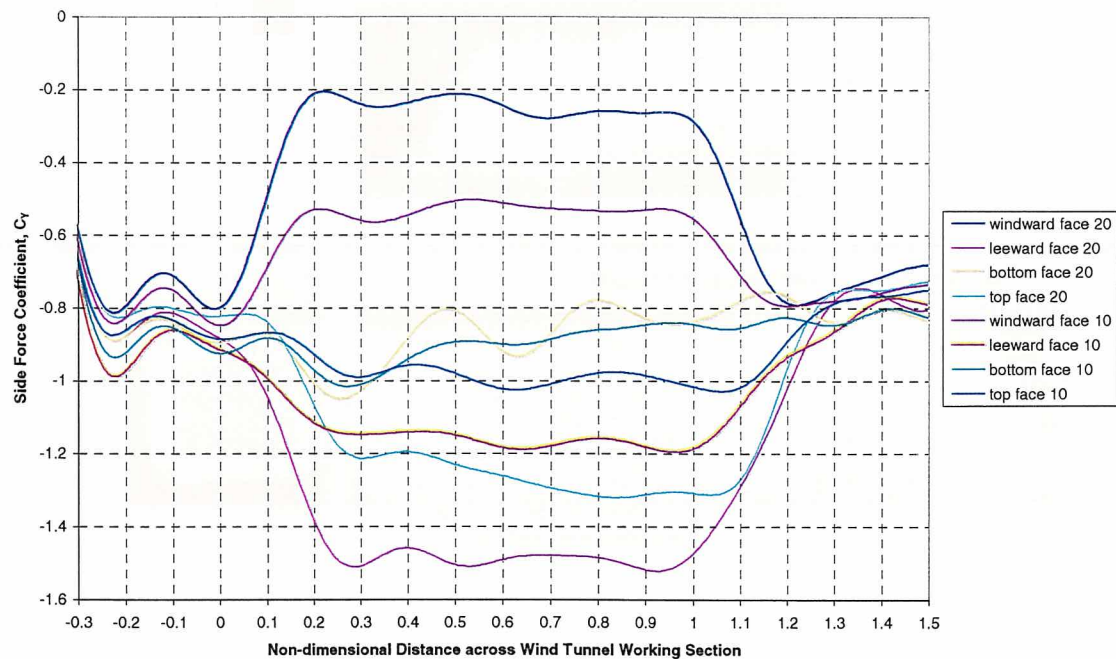


Figure 7-19 Changes in Radiused Edged 1-Box Model Force Coefficients Calculated from Dynamic Pressure Tests

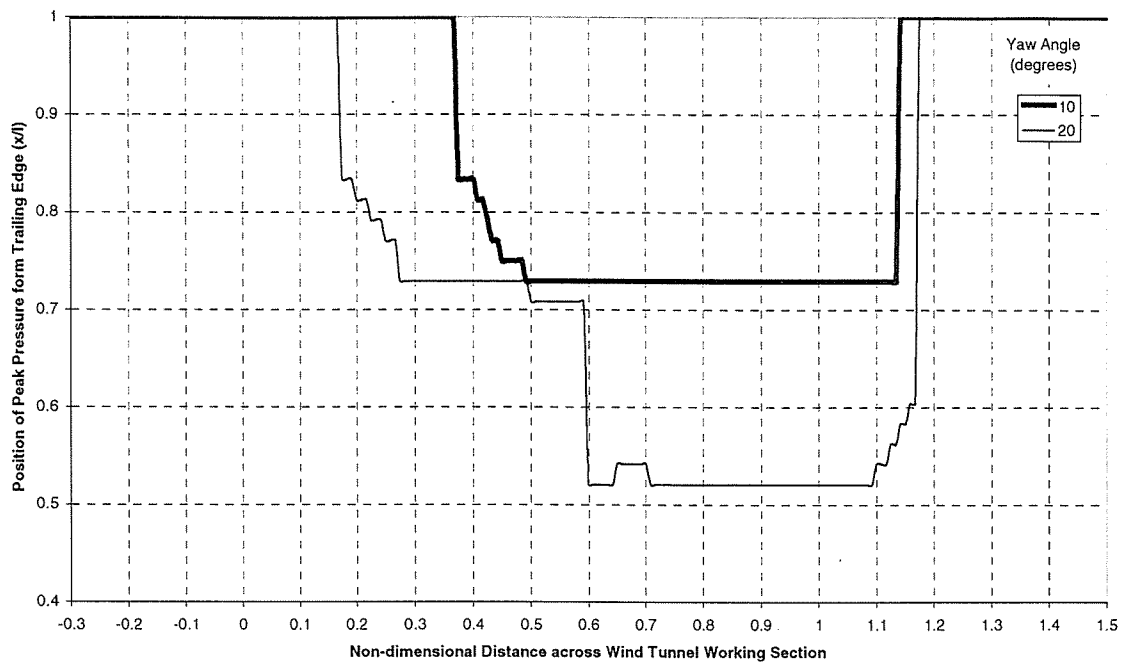


Figure 7-20 Position of Radiused Edged 1-Box Model Transient Peak Pressures on Leeward Face

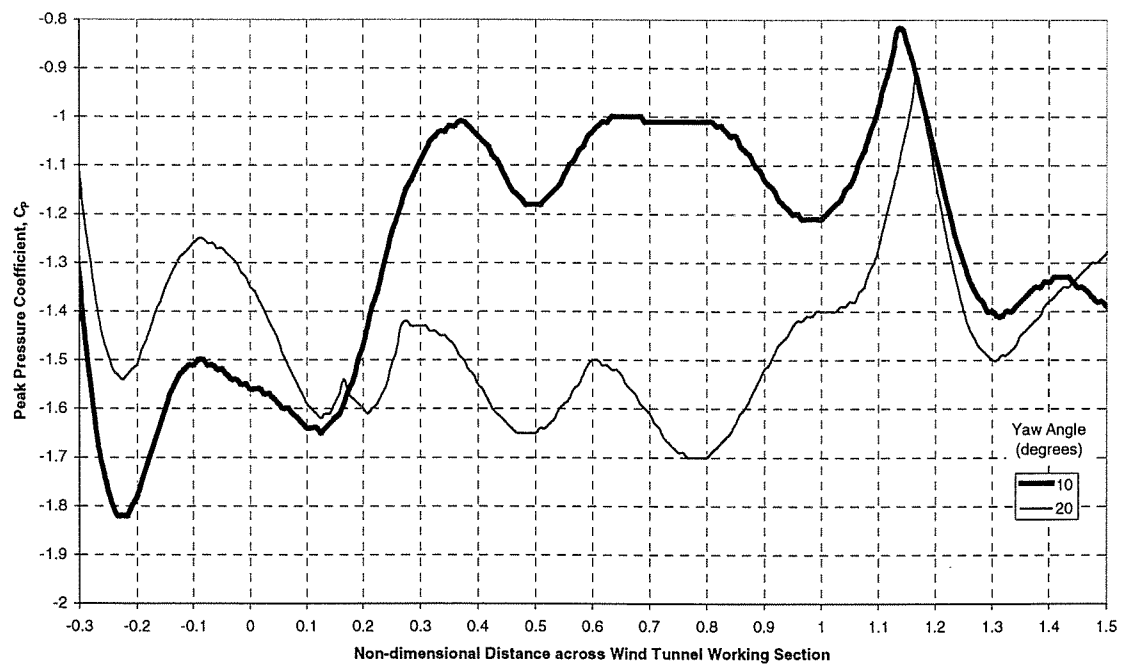


Figure 7-21 Position of Transient Peak Pressures on Leeward Face for Radiused Edged 1-Box Model

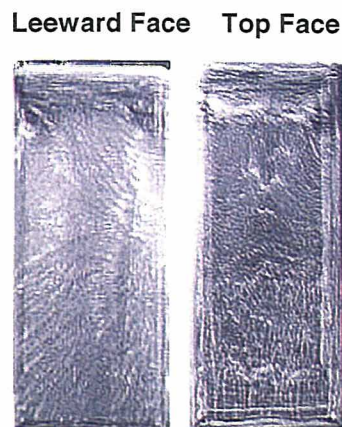


Figure 7-22 Radiused Edged 1-Box Model Flow Visualisation by Surface Paint at 0° Yaw Angle

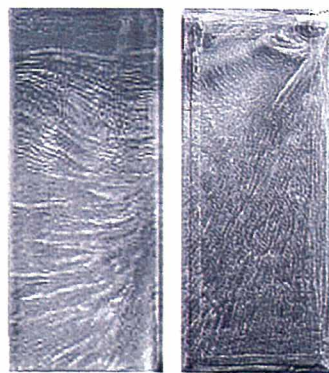


Figure 7-23 Radiused Edged 1-Box Model Flow Visualisation by Surface Paint at 10° Yaw Angle

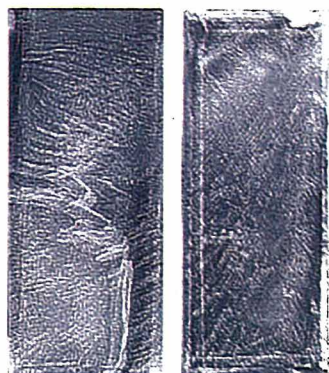


Figure 7-24 Radiused Edged 1-Box Model Flow Visualisation by Surface paint at 20° Yaw Angle

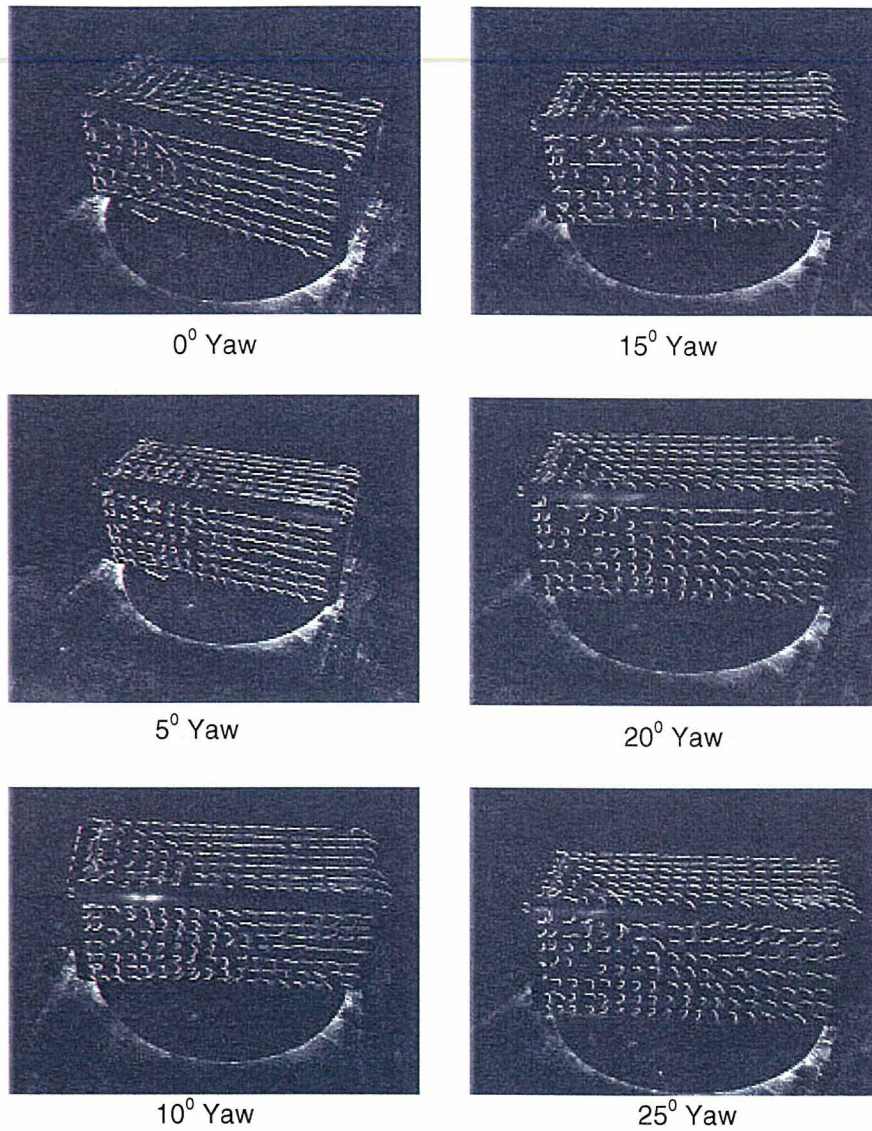


Figure 7-25 Radiused Edged 1-Box Model Flow Visualisation by Fluorescent Tuft 0 - 25° Yaw Angle

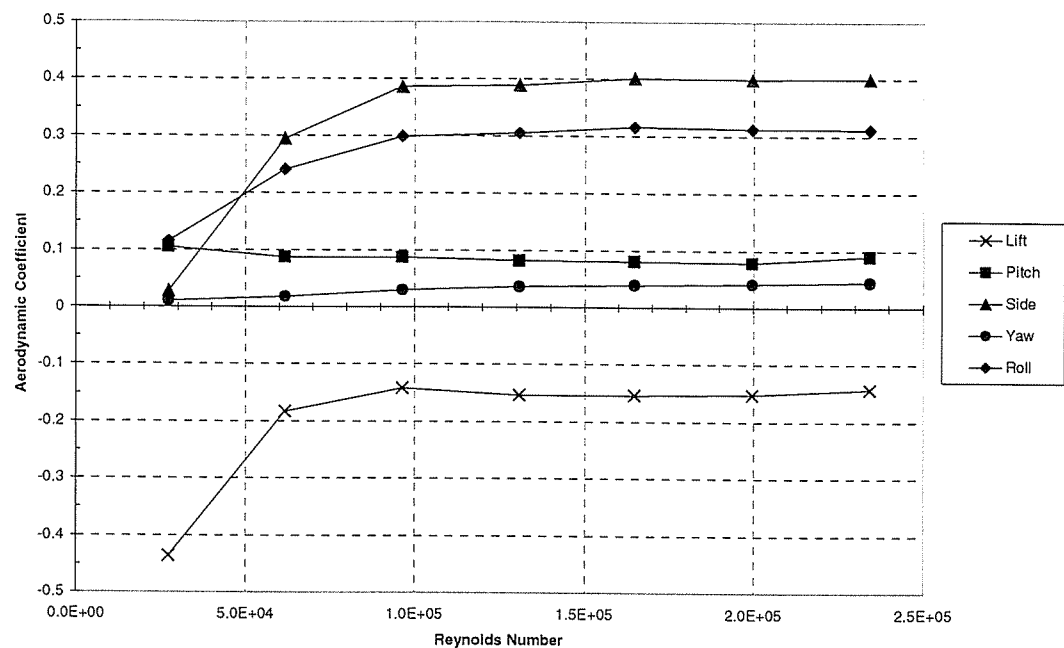


Figure 7-26 Reynolds Sensitivity for Radiused Edged 1-Box Model at 5° yaw angle

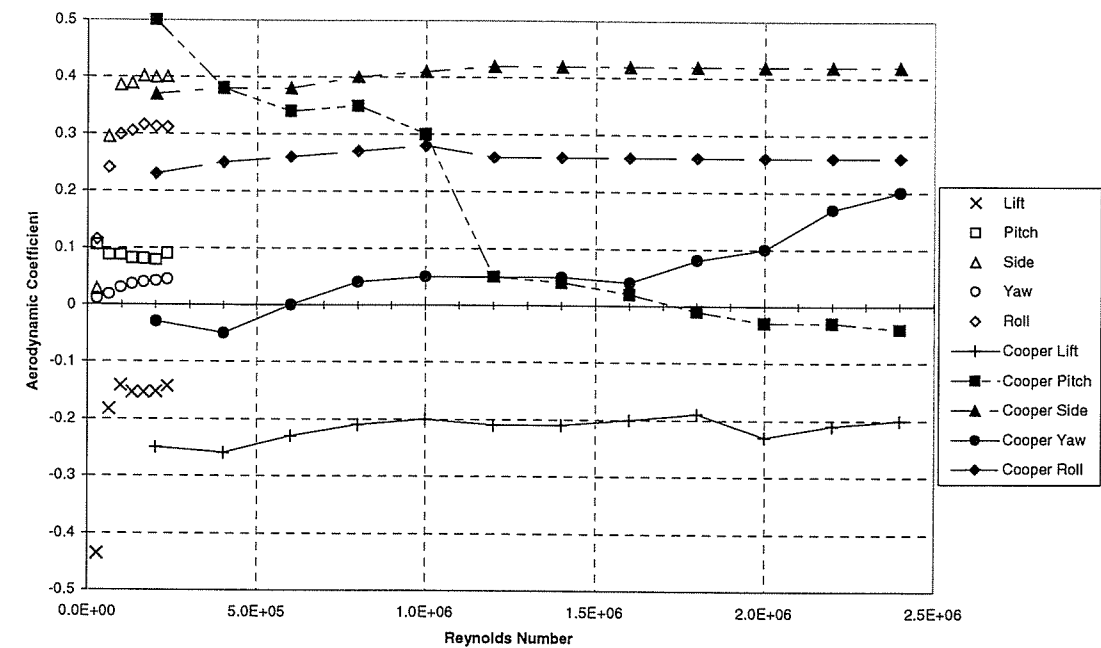


Figure 7-27 Comparison of Reynolds Sensitivity for Radiused Edged 1-Box Model

8. Crosswind Aerodynamics of a 2-Box Model

8.1 Introduction

The 2-box model is the first approximation of a sport utility vehicle tested in this research. Body details are not included on the model and no wheels are simulated but exterior dimensions are approximately scaled from the Range Rover model to be tested as the final model in this research. Dimensions of the 2-box model are shown in Figure 4-11.

Steady state lift force and yawing moments are less than the 1-box type models. The reduction in lift force is due to positive pressures acting on the windscreen face and decrease in yawing moment because of a reduction in side area forward of mid axis.

Increased transient responses on the leeward face pressure animations at both 10° or 20° yaw angle can be identified but are not as dominant as seen on the 1-box models. The most significant unsteady pressure changes for the 2-box model occur on the windscreen and bonnet of the model when entering and exiting the crosswind gust.

In this chapter the model arrangement is that described in chapter 4 with a ground clearance of 30mm. All dynamic tests are conducted at approximately 13m/s track speed and the wind tunnel speed varied to give yaw angles of $0 - 25^\circ$ in 5° increments. All steady state tests and flow visualisation of the model was at a wind tunnel speed of 13m/s.

8.2 Results

8.2.1 Force Data

8.2.1.1 Steady State Tests

Figure 8-1 to Figure 8-4 show steady state aerodynamic force and moment coefficients for the 2-box model from $0 - 25^\circ$ yaw. The lift force coefficient is initially negative at zero degrees yaw and there is only a small deviation up to 10° . The lift force coefficient then rises steadily up to 20° where after the rate of variation with yaw angle decreases. Side force and rolling moment coefficients all display an approximate linear response from $0 - 25^\circ$ yaw angle. The most interesting variation with yaw angle occurs in the yawing moment coefficient which shows an initial linear response up to 15° yaw. The rate of variation with yaw angle then significantly decreases up to the maximum yaw angle tested of 25° . This indicates some change in flow structure at and above 15° yaw angle.

8.2.1.2 Dynamic Tests

Dynamic force and moment traces for the aerodynamic coefficients from $5-25^\circ$ yaw angle are shown in Figure 6-6 to Figure 6-10. Side force and rolling moment coefficients display an initial peak 1.5 body lengths ($x/W = 0.3$) after

entering the gust and there is oscillation in both signals thereafter. After exiting both coefficient signatures take 1.5 body lengths ($x/W = 1.3$) to reach the zero yaw condition. The yawing moment and lift force coefficient dynamic traces contain a significant amount of noise and neither reach a steady value during the duration of the gust. Lift force coefficient dynamic traces exhibit similar traits to that seen for the radiused edged box model. At higher angles of yaw there is an initial peak after 2 body lengths ($x/W = 0.4$), which attains a constant value before a marked rise peaking at $\frac{1}{2}$ body length before the gust exit.

Yawing moment traces are very difficult to interpret. There is much unsteadiness in the dynamic traces and no consistent peaks on entrance or exit of the gust. The erratic dynamic traces could be attributed to an error in data collection, but investigations into the source of the noise during these tests suggest that a low frequency vibration originating from the model is the most likely cause. Conclusive proof would require extensive investigation.

Despite the uncertainty of the dynamic traces, the mean values against yaw angle obtained from dynamic tests shown in Figure 8-1 to Figure 8-4 are comparable to the steady state. Side force and rolling moment coefficients show good agreement between steady state and mean dynamic tests, though mean dynamic values are slightly lower. Mean dynamic lift force is higher than the steady state, however, the dynamic mean traces are relative to 0° yaw. If this is accounted for then there is better agreement, though mean dynamic values are still lower at higher angles of yaw. This can be explained by the dynamic data never reaching a steady value during the gust as well as there being different under body flow conditions. Despite the erratic yawing moment dynamic traces, steady state coefficients show a reasonable comparison with mean dynamic coefficients up to 15° yaw where after mean dynamic values are greater. In steady state tests a change in flow structure was identified at 15° yaw and the higher mean dynamic values above this angle indicates that this change has yet to establish itself during dynamic tests.

8.2.2 Pressure Data

Unlike previous surface static pressure contour maps presented in this thesis, the contour maps of the 2-box model are not interpolated to the edge of each face. Instead the limits of the contour maps are at the start of the radiused edge, with the exception of the trailing edge, and are indicated by the white borders around the contour maps. Because of this limitation, force and moment integration are not calculated but the contour maps still provide a detailed picture of the change in flow characteristics with increasing yaw.

8.2.2.1 Steady State

Figure 8-9 to Figure 8-14 show steady state pressure contour maps of the 2-box model for approximately $0 - 25^\circ$ yaw in 5° increments. For the leeward face, a separation bubble develops from the leading edge and at the A-pillar of the model. Negative pressures in these 2 regions steadily increase from 0° yaw up

to the maximum yaw angle tested of 25° . Another region of negative pressure is noticeable along the roof edge of the leeward face above 15° . This is attributable to the development of a longitudinal vortex along this edge caused by flow accelerating over the top face (as identified in previous tests on the 1-box models). A similar longitudinal vortex also develops at the nose of the model and towards the bonnet edge. The windward face shows a steady dissipation of the separation bubble at the A-pillar and leading edges with increasing yaw angle. A slightly positive pressure develops at the lower A-pillar area above 15° .

For the top surface, skewing of the separation bubble at the cantrail occurs up to 25° yaw angle and another region of negative pressure along the top/windward interface develops above 15° . This is due to the development of a longitudinal vortex originating from flow accelerating over the windward edge, as previously seen in pressure contour maps of the 1-box models.

A change in the pressure distribution on the front face is characterised by the movement of the stagnation point towards the windward face with increasing yaw angle. A slightly positive pressure region is present on the windscreen at 0° yaw that then intensifies with yaw angle up to 15° and moves toward the interface with the bonnet. Above 15° , pressures in this region decrease but maintains its position at the windscreen/bonnet interface. Bonnet face changes are coincident with the windscreen face and are dominated by the movement and intensification of a negative pressure region from the midpoint of the bonnet towards the leading edge up to 10° . Progressive skewing of this region towards the leeward edge occurs up to 25° .

The pressure distribution on the bottom face is much the same as that described for the previous 1-box models. Changes with increased yaw are characterised by the skewing of a leading edge separation bubble towards the leeward face and the development of a second negative region behind the supporting strut. A third negative pressure region is also identifiable at the trailing windward interface at 25° yaw.

Steady state force measurements show that there is a sudden change in the yawing moment variation with yaw above 15° yaw angle. Any change in flow structure should then be apparent on the pressure contour maps for the windward, leeward or front faces. The windward face pressures show no exaggerated variation but changes are evident on the leeward and windscreen face. The leeward face shows the development of a negative pressure region caused by the longitudinal vortex at the roof edge above 15° . This would cause a reduction in the yawing moment as seen in the steady state force measurements. In addition, the windscreen face positive pressure region becomes significantly smaller above 15° which would also result in a reduction in the yawing moment as well as lift force coefficients.

8.2.2.2 Transient Pressure Animation

Mean dynamic pressure contour maps at 10° and 20° yaw angle are shown in Figure 8-15 and Figure 8-16 and differ considerably from the steady state. At

10° yaw all negative pressure regions on the leeward, windward and bonnet faces are lesser in magnitude than that observed for the steady state. Skewing of the separation bubble at the roof cantrail has not yet begun and in many respects the mean dynamic pressure contour map at 10° resembles the steady state condition at 5° . The positive pressure region on the front face is greater in magnitude for the dynamic tests as is the windscreen face positive pressure region.

Mean dynamic pressure contour maps at 20° yaw are a better comparison to the steady state condition. For the steady state, the negative pressure region on the leeward face due to the longitudinal vortex originating from the roof is greater in length but both sets of data exhibit similar trends. Front face pressures are greater in magnitude and cover a greater area for the dynamic contour maps. In addition, the dynamic pressure contour maps do not exhibit strong skewing of the stagnation point as seen in the steady state.

The mean dynamic map on the bottom face at both 10° and 20° is distinctly different from the steady state, most noticeable by the lack of a positive pressure region and separation caused by the supporting strut. This could be due to the gap in the wind tunnel floor to allow passage of the model in dynamic tests, although comparisons for 1-box models between mean dynamic and steady state bottom face pressures have shown good agreement.

Transient animations of the leeward, front and top faces are shown in 2boxlft10.mpeg and 2boxlft20.mpeg. Before entrance to the gust, both animations show increased positive pressure regions on the front and windscreen faces and the leading edge separation region at the bonnet is absent. The leeward face and roof pressure contour maps progressively move toward the steady state pattern on entrance and similarly reduce on exit. There are no sudden pressure changes as previously seen on the sharp and radiused edged box models. It is possible that this is due to the resolution of the pressure tapping grid and further analysis into the pressure changes at individual pressure tappings was performed. Figure 8-17 shows these pressure changes at selected points along the A-pillar. Contrary to the animations, these traces show that there are definite peaks in pressure at the gust entrance. In addition, the pressure coefficient value at $\frac{3}{4}$ from the base of the A-pillar also shows a minimum peak when the model exits the gust. This behaviour is similar to that seen for the leeward vortex collapse of the 1-box models and is evidence of the collapse of the A-pillar vortex although it is not reproduced at other measurement points. Further analysis of pressure tappings at the leeward fender showed that there is some evidence of a leeward separation bubble collapse though is not conclusive since there is much unsteadiness throughout the gust duration.

The windscreen and bonnet faces are now dominant areas of transient activity. On entrance, the windscreen peak positive pressure initially moves towards the leeward face, before "splitting" and moving to the windward edge. On exit the stagnation point again moves back towards the leeward face before attaining the zero yaw condition. The movement of the stagnation point would contribute to any minimum peaks in yawing moment at the gust exit.

Transient pressure contour maps of the windward and bottom faces are shown in 2boxwbf10.mpeg and 2boxwbf20.mpeg. The bottom faces show a skewing of the leading edge separation bubble on entrance and the development of an area of negative pressure on the leeward side of the supporting strut. On the windward face the growth and dissipation of a region of positive pressure extending from the windscreen to towards the bonnet is the only discernible feature.

8.3 Discussion

8.3.1 Previous Work

A comparison of previous work on 2-box type models will be made together with the Range Rover model results in chapter 9. A feature that presented itself in these tests was the change in yawing moment above 15° and which was also recorded by Kohri⁴⁵ on a notchback type vehicle. Changes in yawing moment and side force coefficients with yaw were classified into two distinct regions. In region 1 below 22° yaw angle the flow is characterised by vortices at the leeward front corner, A-pillar and windward C-pillar. Separation and reattachment of the flow occurs and negative pressure is generated between these points. In the second region above approximately 22° separation of the flow starts to occur and the corner vortex at the A-pillar disappears. The negative pressure created by the vortex is thus released and an improvement in the yawing moment coefficient is made. This explanation given by Kohri does not fit in with the present results possibly due to the different vehicle shapes, though pressure changes at the A-pillar should be approximately the same regardless of rear end configuration. In the present results there is no evidence of A-pillar separation and the change in yawing moment is due to the negative pressure region (caused by the longitudinal vortex generated at the top edge) moving progressively towards the trailing edge with increasing yaw angle.

8.3.2 Comparison with other Models in the Current Research

Steady state lift force and yawing moments are less than the 1-box type models. For the lift force the reduction is due to positive pressures acting on the windscreen face, the vertical component of which would be negative lift. Differences in yawing moment can be explained by the reduction of side area forward of mid axis.

A comparison between the steady state and mean dynamic pressure contour maps revealed many inconsistencies previously not seen with other models. The step from 1-box to 2-box type shapes has increased the flow field complexity resulting in increased unsteadiness of measured pressures. This is evident in measured force and moment coefficients that do not reach a steady value within the time it takes to cross the gust.

Of interest is the movement of the stagnation point on the windscreen and front face as the model enters and exits the gust and which has also been previously

seen on the sharp and radiused edged 1-box models. The effect of the movement would be to cause a decrease in the yawing moment coefficient, but the movement of the stagnation point to the leeward face is completely unexpected and still requires further investigation.

Probably the most significant result revealed during the testing of the 2-box model is that the increased transient responses as seen in previous models, most notably the growth and collapse of the leeward separation bubble on gust entrance and exit, are not in evidence. This could be because the pressure tapping grid sizing was not of a high enough resolution to capture this data. Changes in pressure at individual measurement points do show evidence of a leeward leading edge separation bubble collapse at gust exit and also increased pressures along the A-pillar at the gust entrance.

8.4 Conclusions

The conclusions that can be made from tests on the 2-box model are:

1. Steady state side force and rolling moments display an approximate linear relationship with increasing yaw. Changes in lift force and yawing moment coefficients are more complex.
2. Changes in steady state yawing moment above 15° are due to the development of the longitudinal vortex along the roof edge causing negative pressures to act rearward of mid axis and consequently stabilising the yawing moment.
3. Steady state lift force and yawing moments are less than the 1-box models:
 - Lift force reduction is due to positive pressures acting on the windscreen
 - Yawing moment reduction is due to the reduction of front side area
4. Increased transient responses of the leeward face at gust entrance and exit are not as pronounced as that seen on a 1-box type model.
5. Examination of individual pressure tappings showed that the pressures at the A-pillar increased on entrance which would result in an increased yawing moment. Unfortunately, moment data is corrupted by noise and increased responses at the gust exit are hard to define for all yaw angles.
6. The windscreen face of the 2-box model shows significant transient activity and is seen to interact with changes in pressures on the leeward face

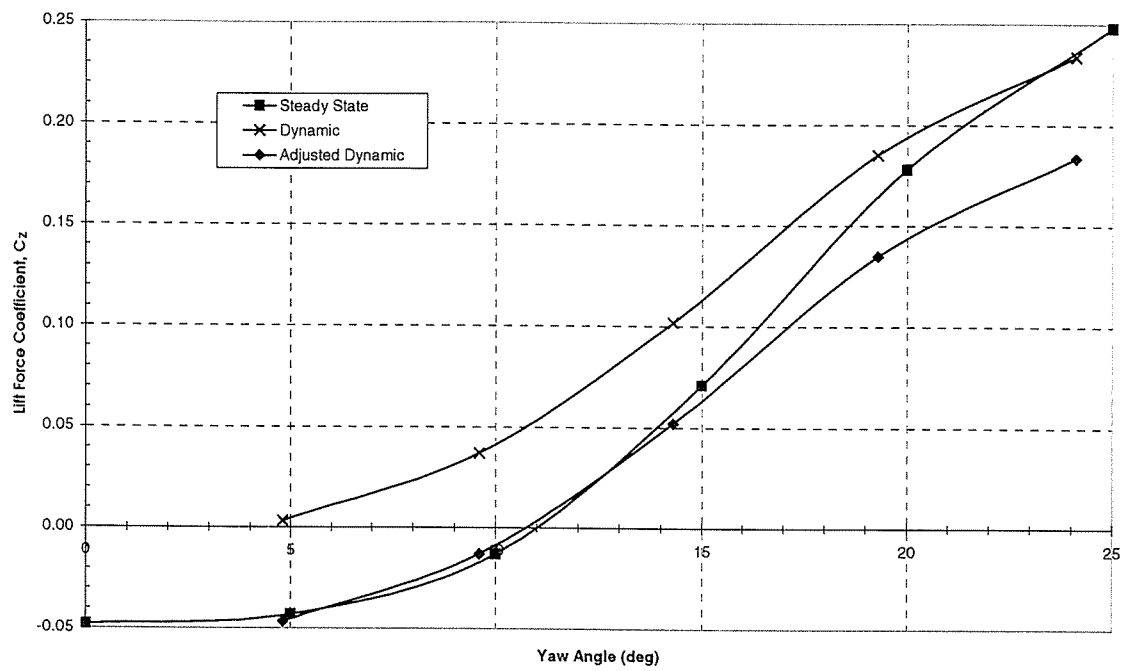


Figure 8-1 Variation of Lift Force Coefficient with Yaw Angle for 2-Box Model

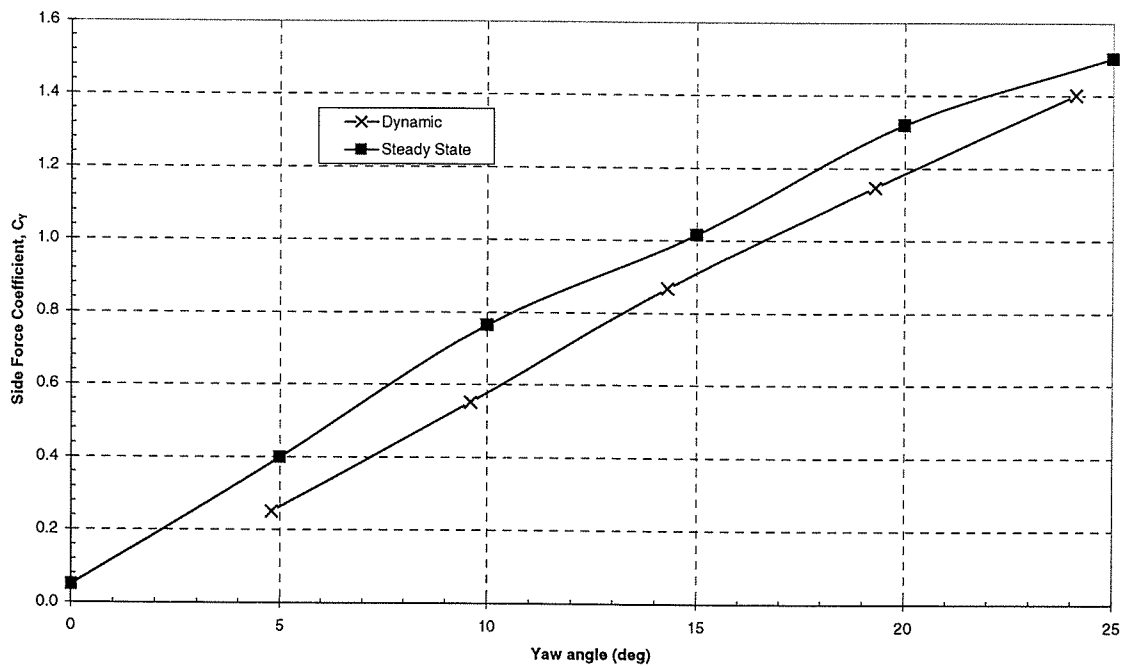


Figure 8-2 Variation of Side Force Coefficient with Yaw Angle for 2-Box Model

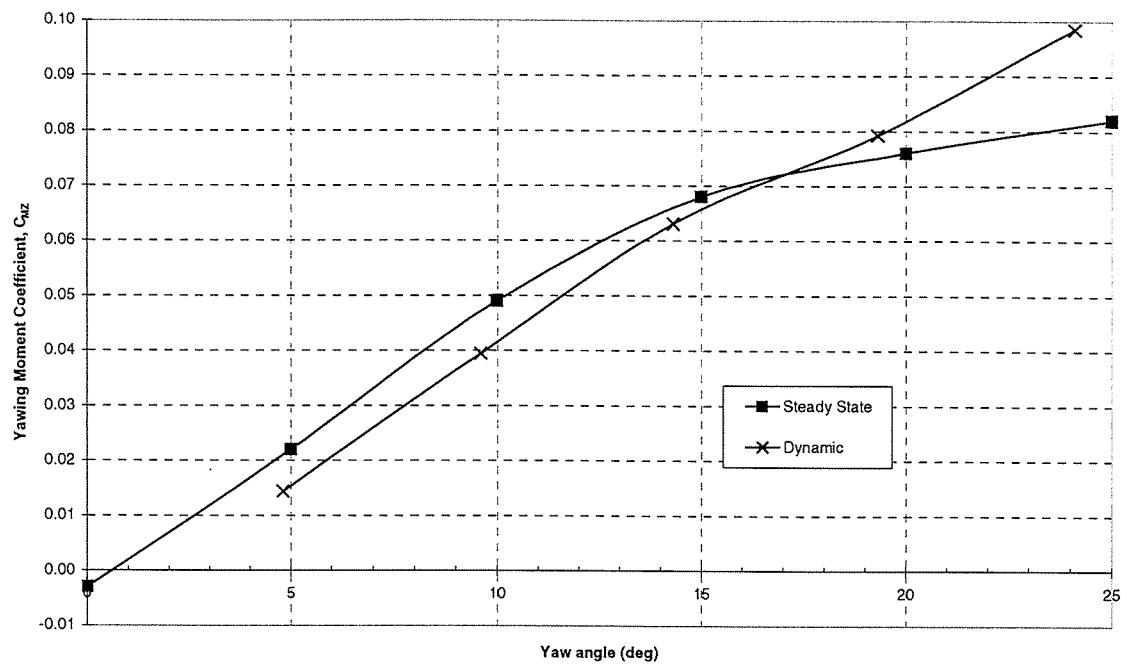


Figure 8-3 Variation of Yawing Moment Coefficient with Yaw Angle for 2-Box Model

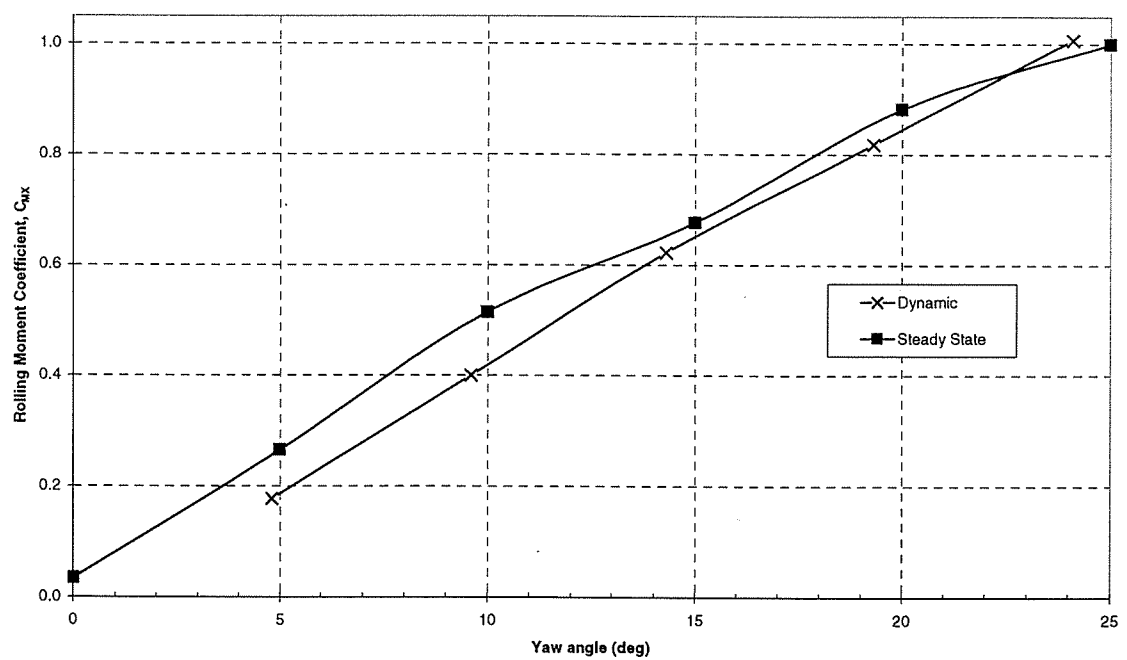


Figure 8-4 Variation of Rolling Moment Coefficient with Yaw Angle for 2-Box Model

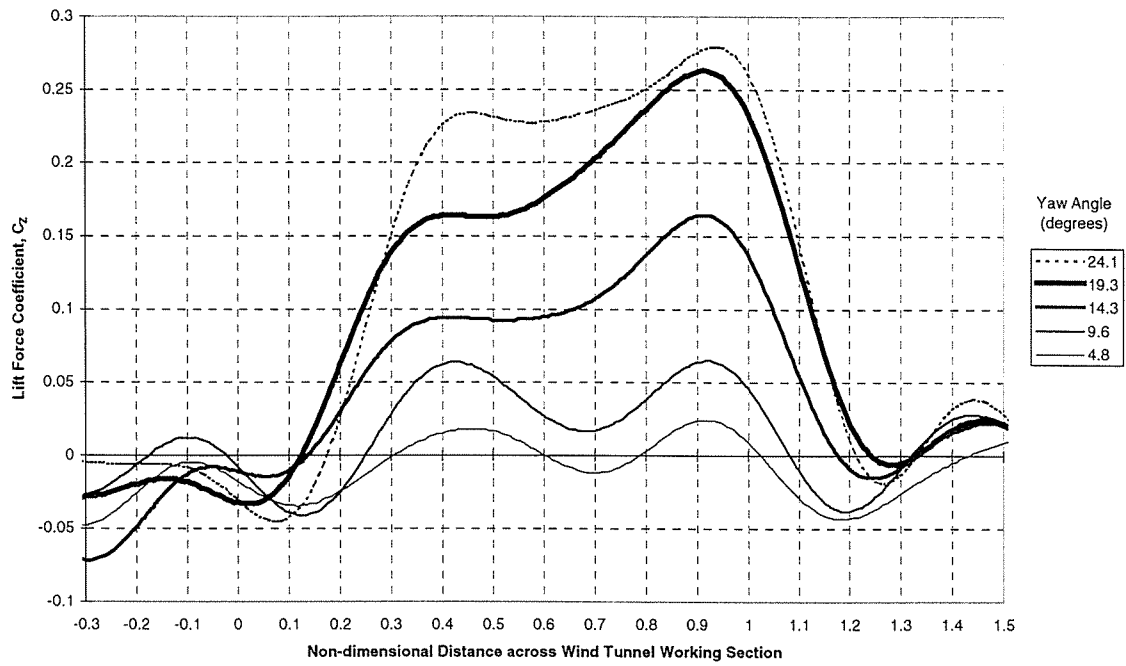


Figure 8-5 2-Box Model Lift Force Coefficient Dynamic Traces for 5 - 25° Yaw Angle

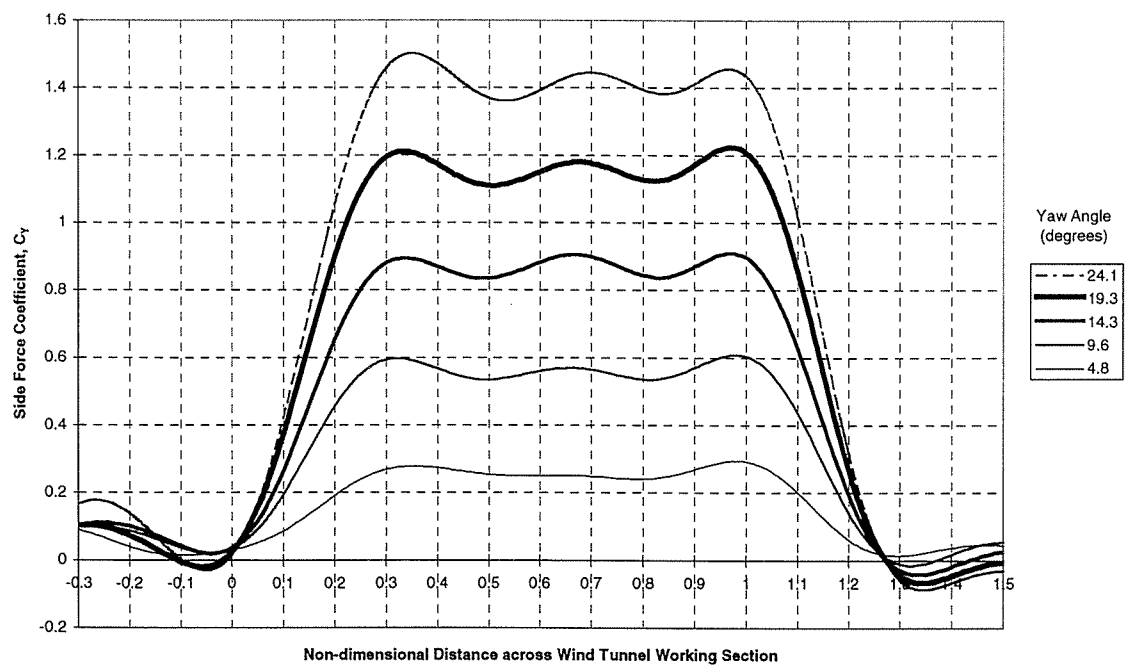


Figure 8-6 2-Box Model Side Force Coefficient Dynamic Traces for 5 - 25° Yaw Angle

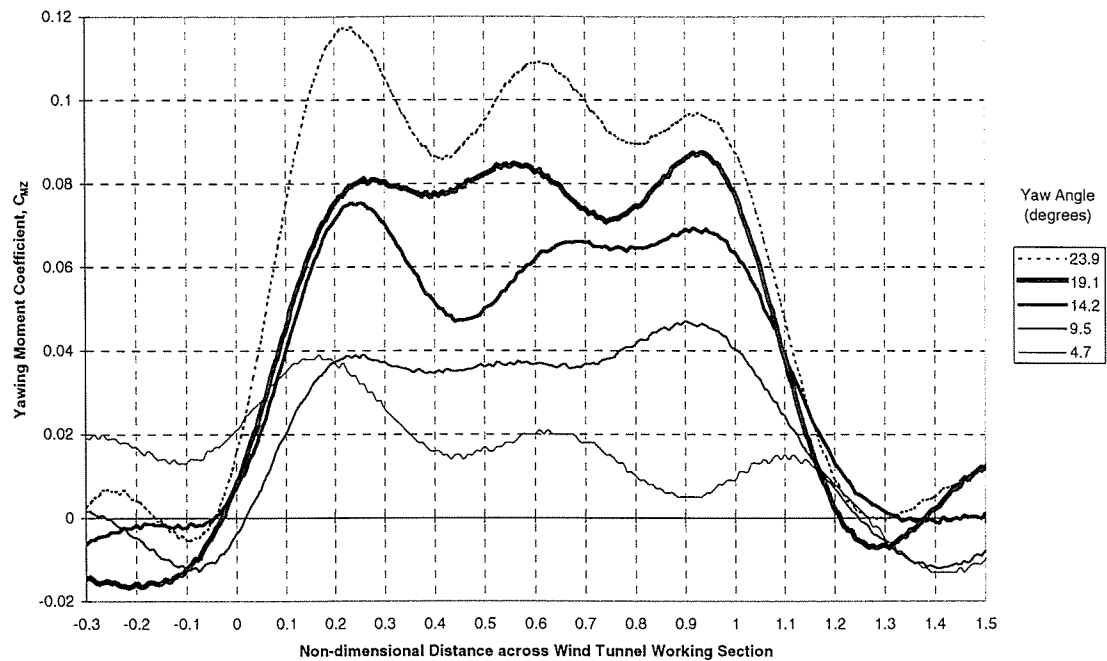


Figure 8-7 2-Box Model Yawing Moment Coefficient Dynamic Traces for 5 - 25° Yaw Angle

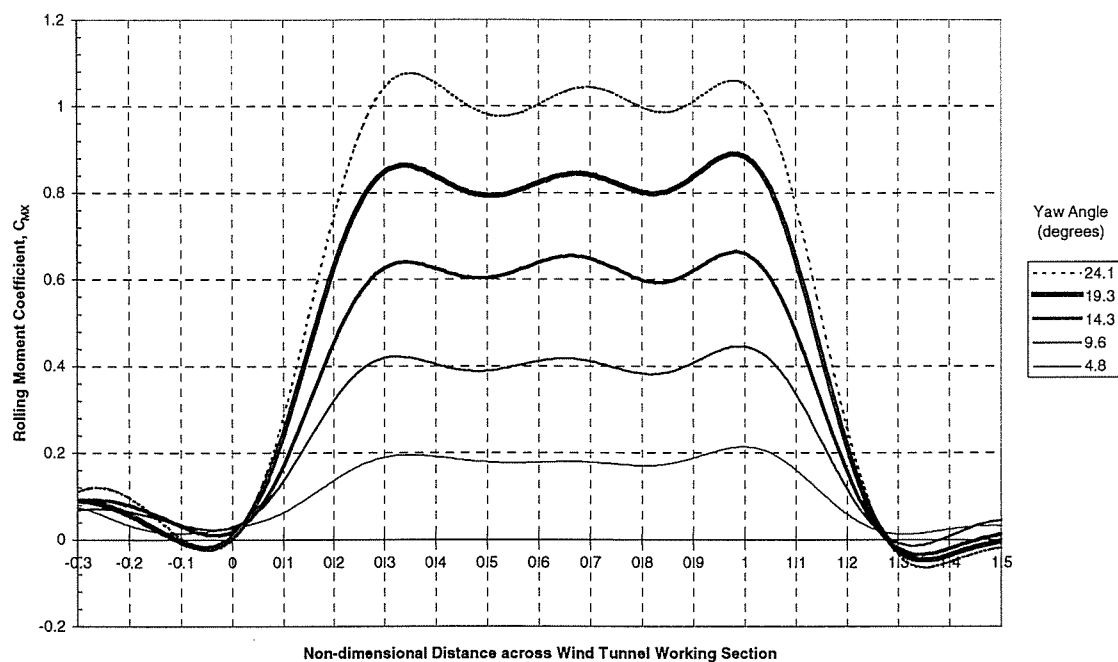


Figure 8-8 2-Box Model Rolling Moment Coefficient Dynamic Traces for 5 - 25° Yaw Angle

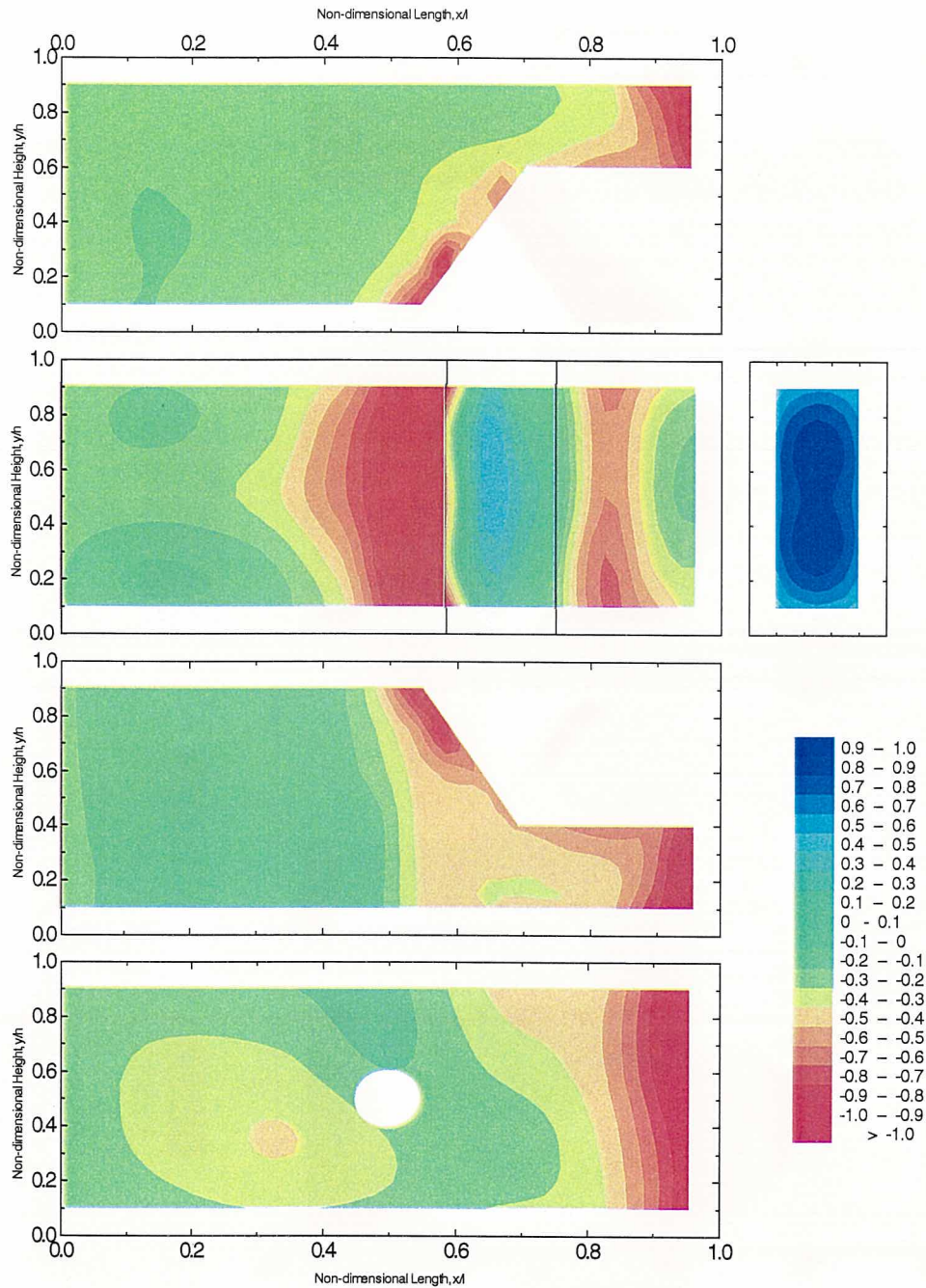


Figure 8-9 Steady State 2-Box Pressure Contour Map at 0° Yaw Angle. Leeward Face at Top of Page

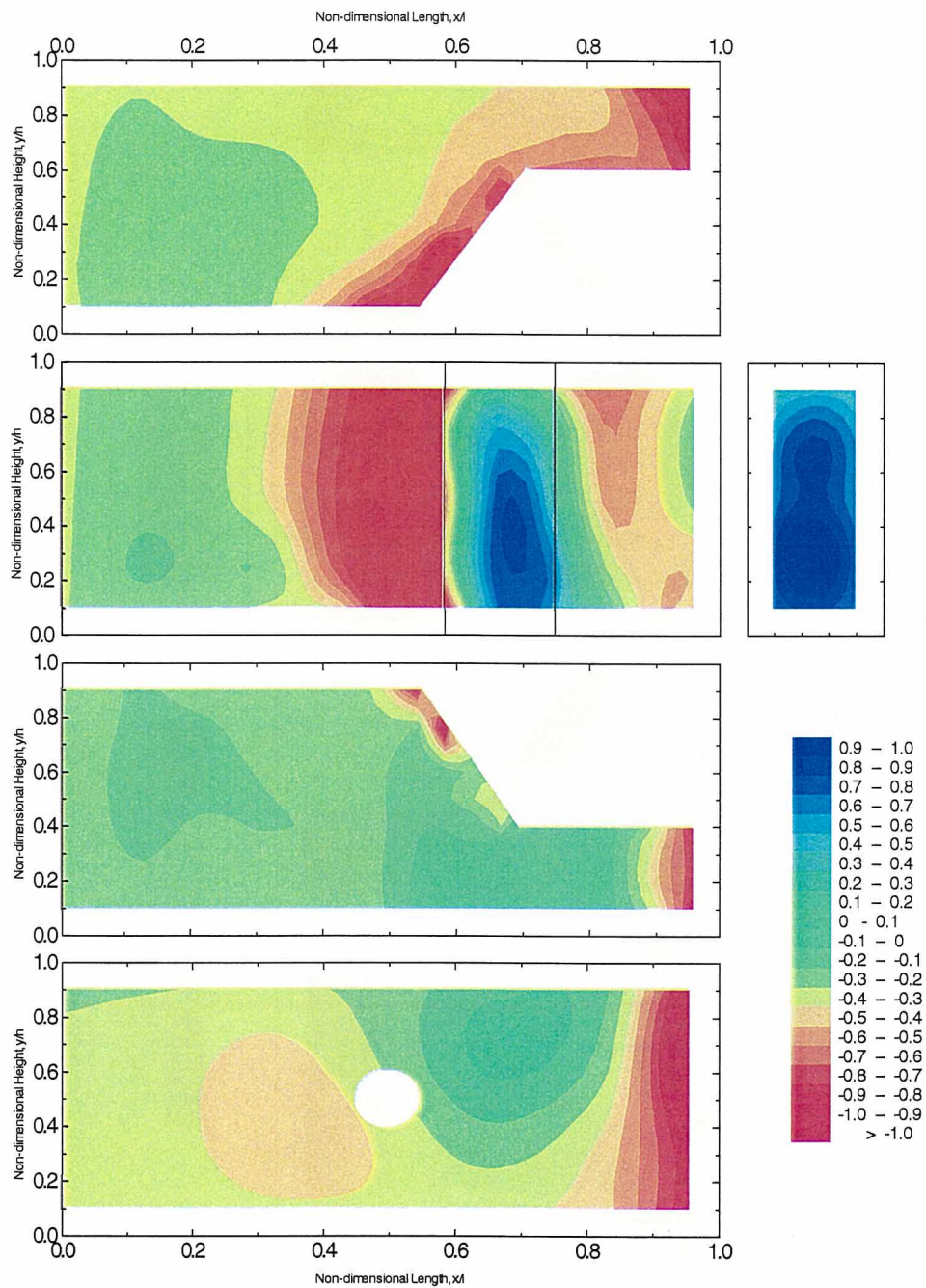


Figure 8-10 Steady State 2-Box Pressure Contour Map at 5° Yaw. Leeward Face at Top of Page

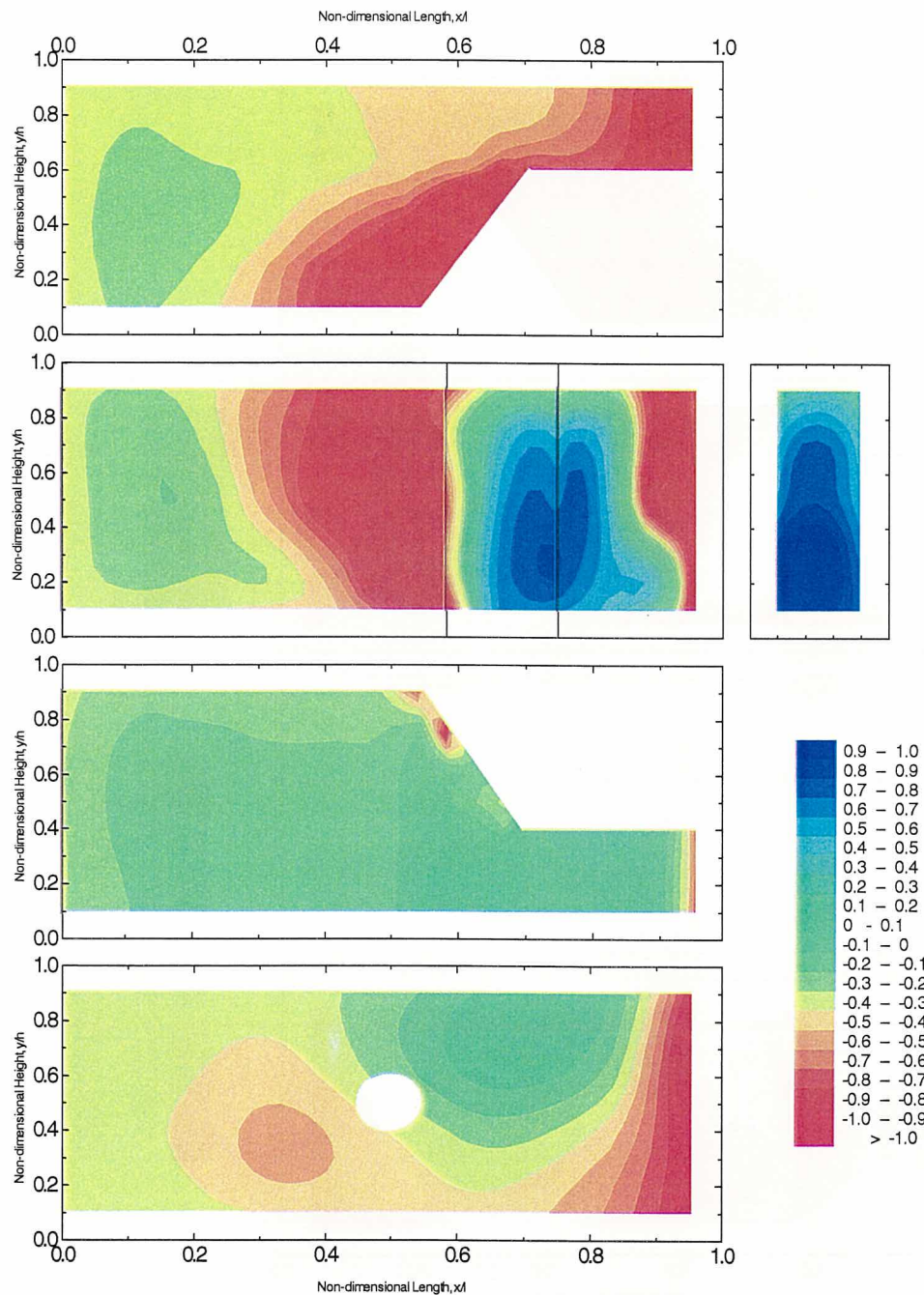


Figure 8-11 Steady State 2-Box Pressure Contour Map at 10° Yaw. Leeward Face at Top of Page

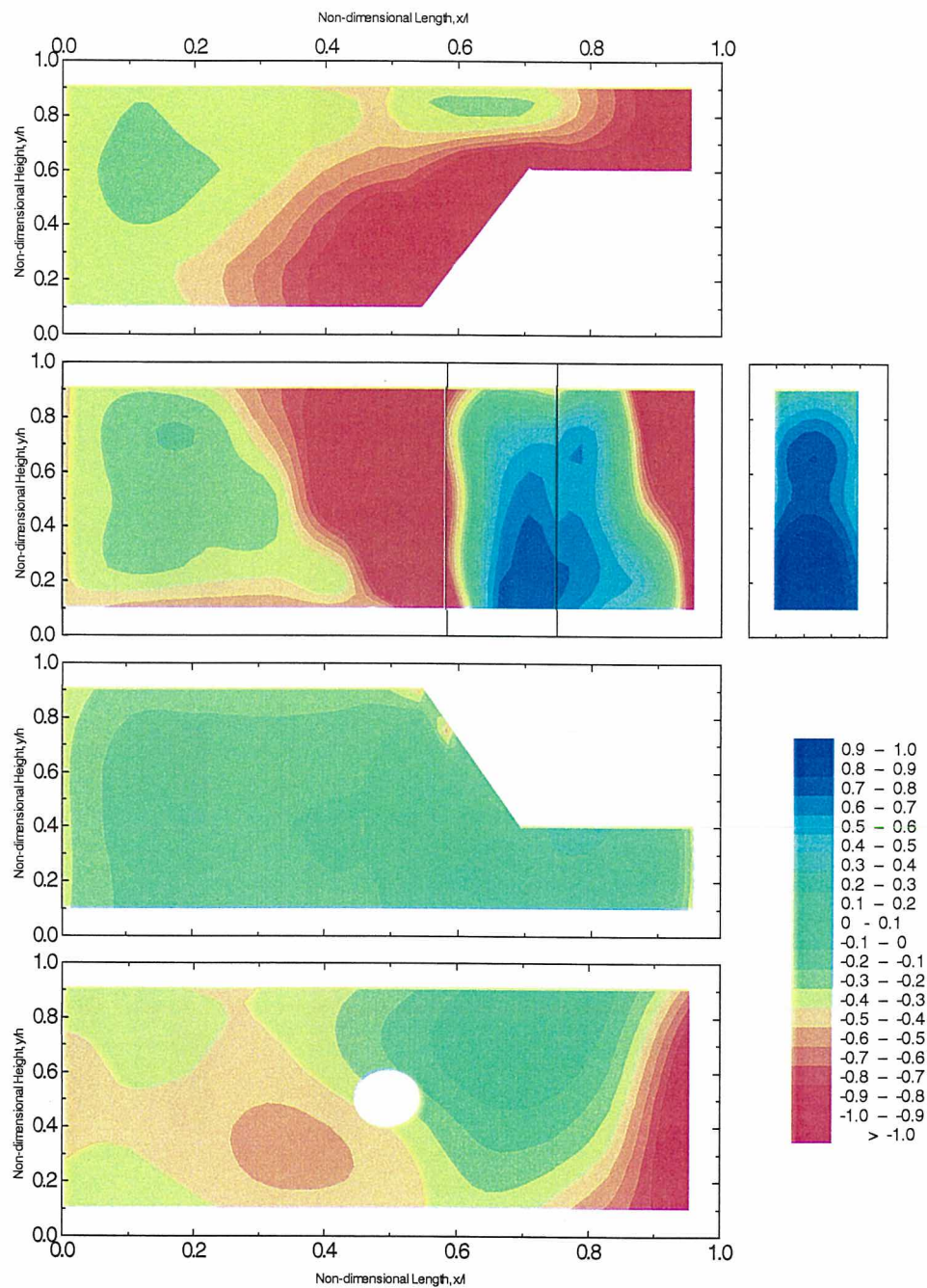


Figure 8-12 Steady State 2-Box Pressure Contour Map at 15° Yaw. Leeward Face at Top of Page

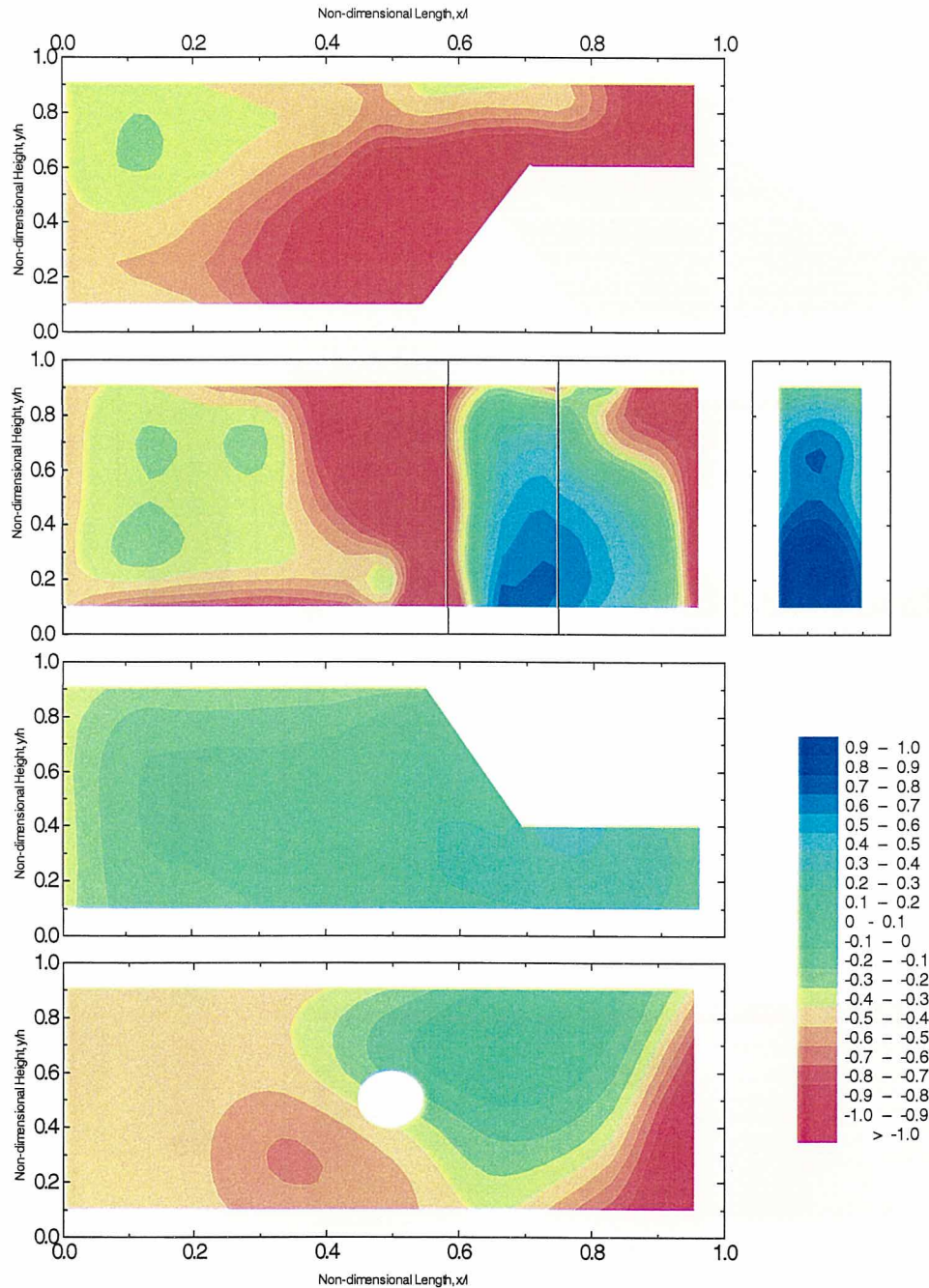


Figure 8-13 Steady State 2-Box Pressure Contour Map at 20° Yaw. Leeward Face at Top of Page

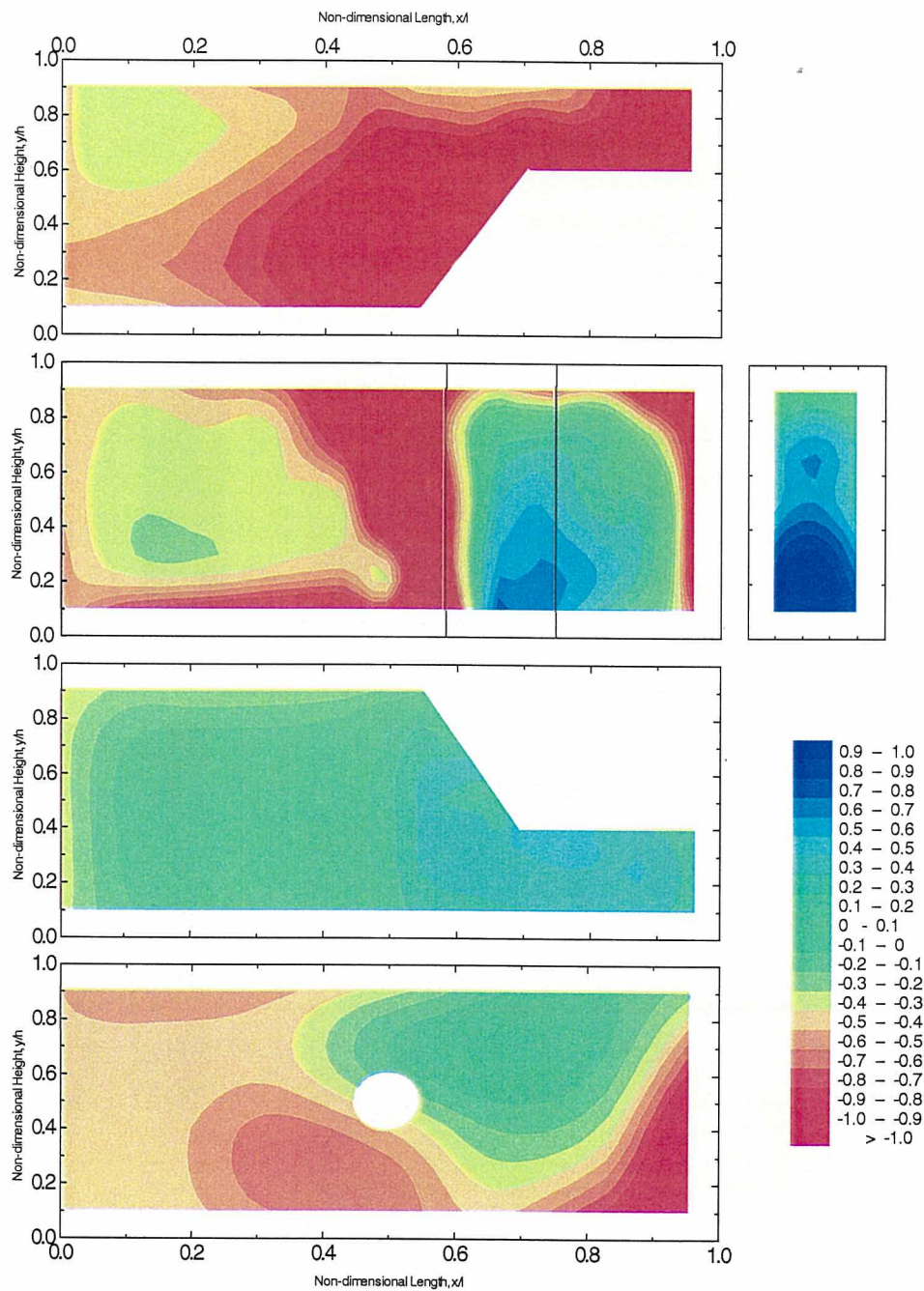


Figure 8-14 Steady State 2-Box Pressure Contour Map at 25° Yaw. Leeward Face at Top of Page

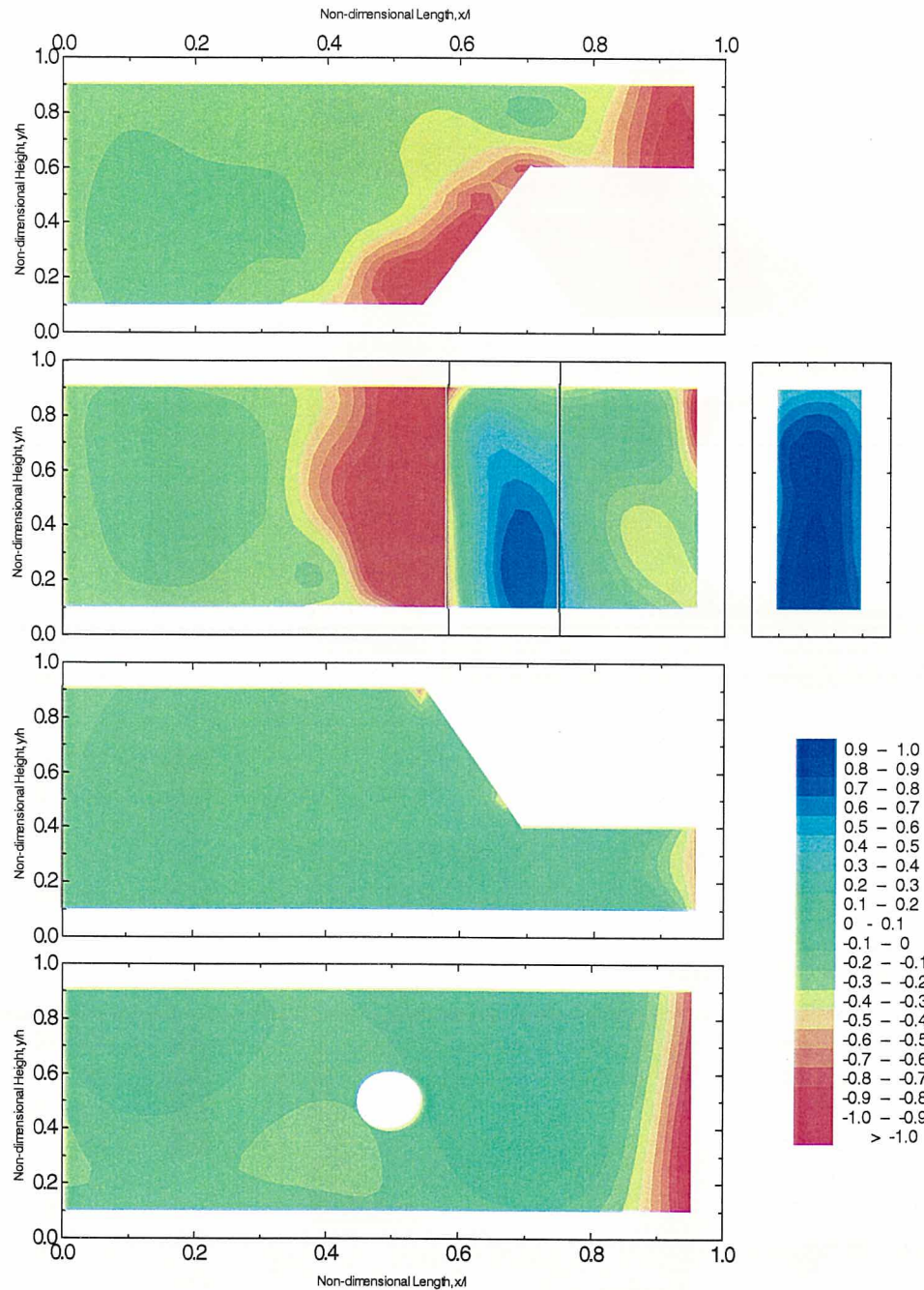


Figure 8-15 Mean Dynamic 2-Box Pressure Contour Map at 10° Yaw. Leeward Face at Top of Page

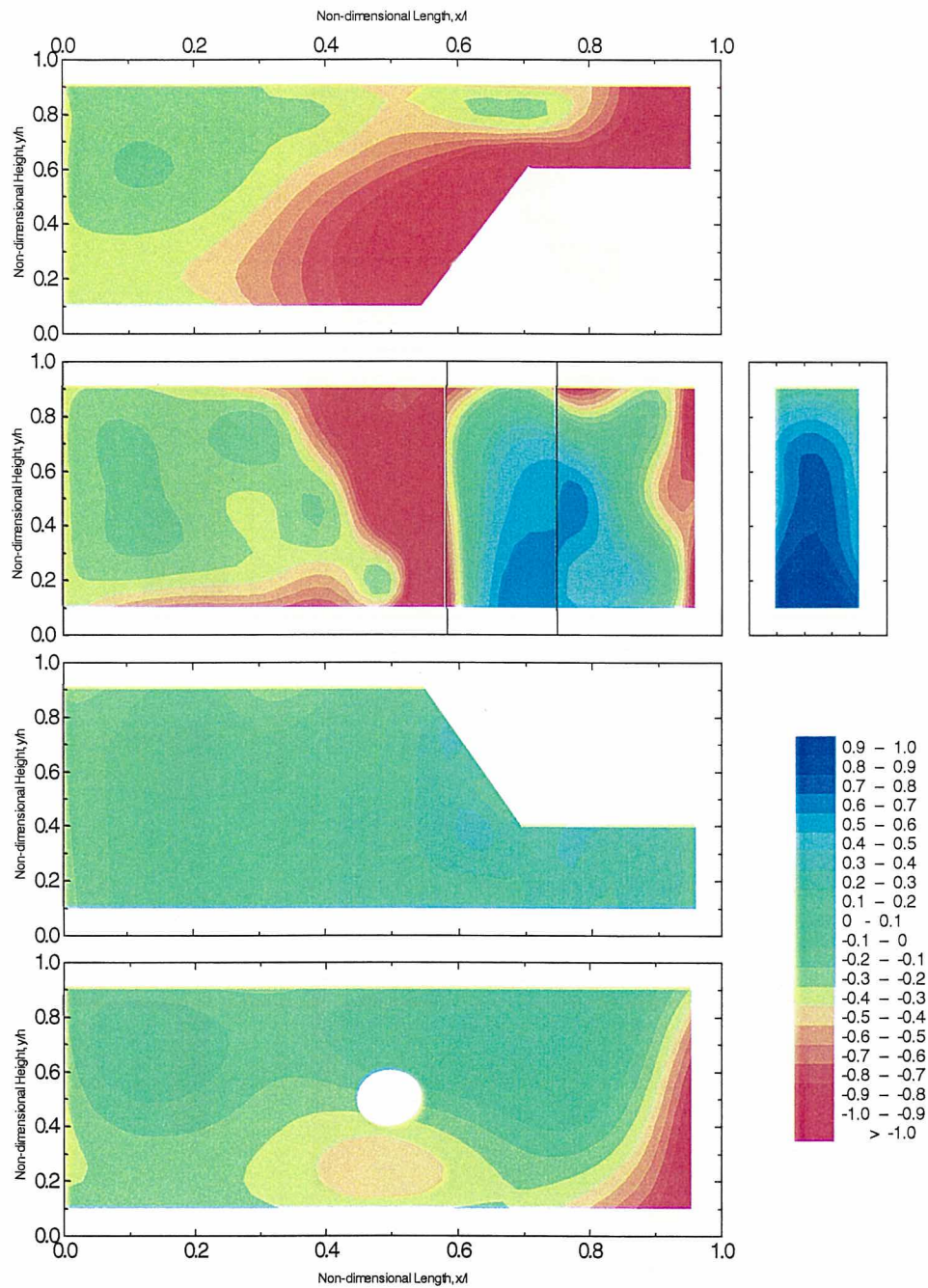


Figure 8-16 Mean Dynamic 2-Box Pressure Contour Map at 20° Yaw. Leeward Face at Top of Page

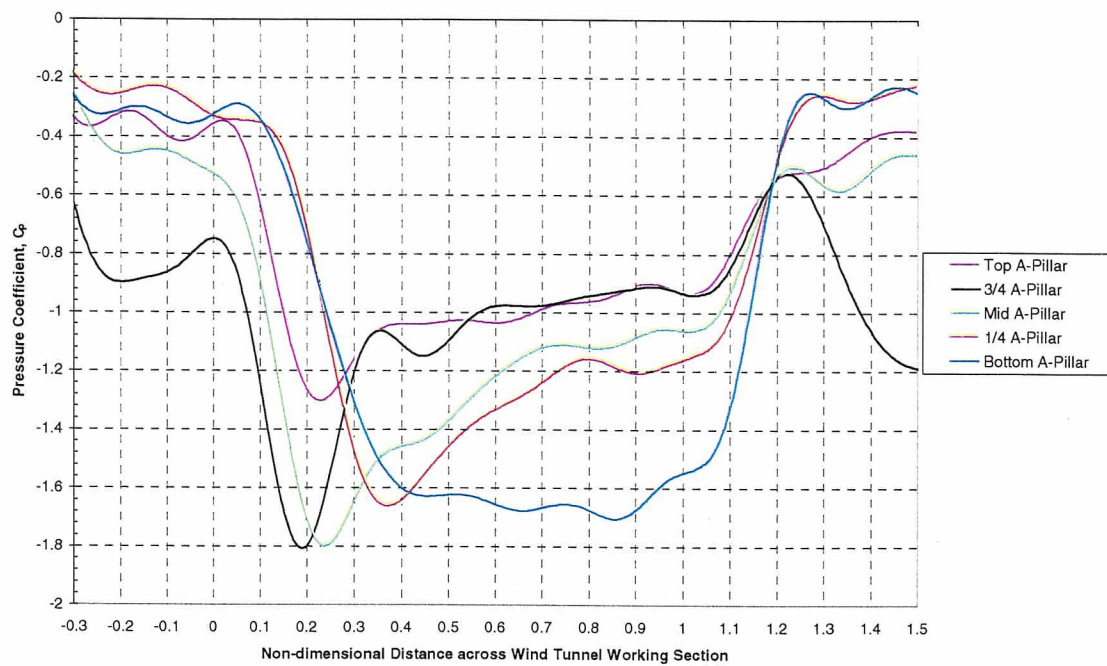


Figure 8-17 Changes in Pressure Coefficient along the A-Pillar

9. Crosswind Aerodynamics of a Sports Utility Vehicle

9.1 Introduction

The final model to be tested during this research program was of a nominally 1/8 scale model 1996 production Range Rover (Figure 4-13). All body details excepting wing mirrors are included. Wheels are fixed to the vehicle body and do not rotate and the model has a smooth underfloor.

The results are similar to those recorded on the 2-box model in side and lift force coefficients. Range Rover yawing moment coefficients are greater than the 2-box model and rolling moment coefficients are lower. In dynamic tests, peak yawing moments are 1.25 times greater than the mean value.

Transient pressure tests showed that there is sudden change in leeward fender pressures at the gust entrance. There are also minimum peaks in pressure at the A-pillar as the model exits the gust. None of the transient responses identified are as pronounced as other models tested.

In this chapter the model arrangement is with a wheel ground clearance between 1 and 4mm. All dynamic tests are conducted at approximately 14m/s track speed and the wind tunnel speed varied to give yaw angles of 0 – 25° in 5° increments. All steady state tests of the model were conducted at a wind tunnel speed of 14 m/s.

9.2 Results

9.2.1 Force Data

9.2.1.1 Steady State Tests

Figure 9-1 to Figure 9-4 show mean aerodynamic force and moment coefficients for the Range Rover model from 0 – 25° yaw, together with full-scale data recorded by Docton. Differences between the present model and full-scale are that the underbody is smooth plus minor changes in body details. The lift force coefficient for the model is negative at zero degrees yaw then rises steadily with increasing yaw angle up to 15° where after the rate of change of coefficient with increasing yaw angle increases. All lift force data is lower than recorded by Docton, this is assumed to be due to the difference in underbody flow. A smoother underbody encourages higher flow velocities and hence lowers pressure and leads to lower overall values of the lift force coefficient. Side force and yawing and rolling moment coefficients for the model all display an approximate linear response from 0–20° yaw angle. The rate of variation with yaw angle then decreases slightly up to 25°. Side force and yawing moment coefficients are both greater than recorded at full-scale, although the change in yawing moment above 20° is also present at full-scale. No comparison is available for rolling moment.

9.2.1.2 Dynamic Tests

Dynamic traces of the aerodynamic coefficients are shown in Figure 6-6 to Figure 6-10. Pitching moment data is not included because vibration noise in the signal made the results difficult to interpret. The overall response of the aerodynamic force and moment data is similar to that previously seen for the 2-box model but with less unsteadiness in the dynamic traces. It is unsure if this is an aerodynamic effect or due to different model construction techniques

Side force and rolling moment coefficients exhibit little variation for the duration of the gust for all yaw angles, though peaks in data occur after 1.5 body lengths ($x/W = 0.3$) after the nose of the model enters the gust and also at the gust exit. At higher yaw angles, the yawing moment coefficient has a clearly defined peak at 1 body lengths ($x/W = 0.2$) after the nose of the model enters the gust. The coefficient value then drops rapidly up to 2.5 body lengths ($x/W = 0.45$) before rising again up to the gust exit. An overshoot is noticeable for all yaw angles at 1.25 body lengths after exiting the gust.

Lift force dynamic traces are the most complex to decipher. There is considerable unsteadiness at lower angles of yaw and the coefficient never reaches a steady value even after gust exit. At 20° and 25° yaw, response is characterised by a significant peak on entrance at 1.5 body lengths ($x/W = 0.3$) and an even greater peak just before the gust exit. This 2 peak behaviour has been previously observed on 1-box and 2-box models. Examination of the 2-box model transient animation for the roof (2boxlft20.mpeg) and lift force coefficient dynamic trace (Figure 9-5), show that the initial peak is determined by peak pressures occurring in the leading edge separation bubble before a negative pressure region towards the rear windward quarter of the roof has been established. This negative pressure region is caused by the longitudinal vortex originating from the windward face.

Comparisons of mean dynamic and steady state variation with yaw is included in the traces of Figure 9-1 to Figure 9-4. Rolling moment and side force coefficients show excellent agreement for all yaw angles. Mean dynamic yawing moment data is slightly lower, but this must be tempered with the fact that the coefficient never reaches a steady value throughout the gust width. This is also true for the lift force coefficients where unsteadiness is even greater. Even so the mean dynamic and steady state coefficients show comparative values for all yaw angles.

9.2.2 Pressure Data

Full surface static pressure contour maps of the range rover model have not been completed. This is mainly because the results of the 2-box model tests showed that the effort required in programming the Fieldview grids would not be that beneficial. Instead a line of 10 pressure tappings was placed on the leeward face and along a line from the front bumper to bonnet edge and up the A-pillar. The positions of the Range Rover model pressure tappings are shown in Figure 4-13.

Plots of the line of surface static pressure tappings at yaw angles $0 - 25^\circ$ are shown in Figure 9-9 and Figure 9-10. Starting at the top of the A-pillar, tapping numbers 10 and 9 show little variation with increasing yaw angle. Tapping 7 placed towards the bottom of the A-pillar is very unsteady and was also observed in the transient animations for the 2-box model. Tappings 6, 5 and 3 situated below the bonnet and leeward edge all show increases in the pressure coefficient up to 20° and then a small decrease in the pressure coefficient value up to 25° . Significant changes in surface static pressure can be seen in tapping 4 which is also located along this edge. The change of pressure coefficient against yaw angle for tapping 4 shows a similar response to other tappings along the bonnet/leeward interface but with a trough occurring at 20° yaw. Pressure coefficients at tapping 2 (located near the leading edge on the leeward face) increase steadily with increasing yaw up to 15° then drop slightly towards 25° and tapping 1 shows a steady increase for all yaw angles. In general, there is a linear variation of pressure coefficients with change in yaw angle at all tappings throughout the yaw angles tested with the exception of 20° (Figure 9-9). The deviation from the overall trend is most noticeable between tappings 3 and 7 which are located along the bonnet/ leeward interface.

Surface static pressure coefficients recorded during dynamic tests at 24° yaw are shown in Figure 9-11. All tappings display unsteadiness during the gust width. The peak in data on gust entrance for tapping 2 (located near the leading edge of the leeward face) is the only increased transient response noticeable for any tappings. It is also noticeable that tapping 4 and tapping 8 take longer to reach a steady state condition. The results from the dynamic tests show that the leeward/bonnet interface is a region of significant transient activity.

A comparison of steady state and mean dynamic pressure coefficients at 25° yaw are shown in the plot of Figure 9-12. The figure shows the excellent agreement between the two measurement methods and also confirms that, for the tappings recorded, a steady state condition is achieved during the gust.

9.3 Discussion

9.3.1 Previous Work

Work that lends itself for immediate comparison is that by Docton⁴⁹ on a full-scale Range Rover from $0-35^\circ$ yaw angle. Steady state aerodynamic force and moment coefficients from Docton are included in Figure 9-1 to Figure 9-4 and have been previously discussed in section 9.2.1.1. A surface static pressure survey for the full-scale model was also performed and from this Docton calculated the relative contribution to side force and yawing moment from different body elements. It was found that the region that generated side force was predominantly at the leeward face A-pillar and then at the leading edge of the leeward fender. Of these, the negative pressure coefficients at the leading edge fender generated the larger yawing moment due to the increased distance from the moment reference point. Peak negative pressures were found to be on the leeward face at approximately $\frac{3}{4}$ distance from the base of the A-pillar. This

result corresponds well with the position of peak pressures observed for the current tests.

In addition to the full-scale tests of Docton, steady state aerodynamic force and moment coefficients of a SUV (unspecified manufacturer) have been recorded by Howell in a full-scale wind tunnel. Force and moment coefficients from these tests and present data compares well. Howell additionally recorded dynamic response from the same vehicle as it passed a crosswind generator. The crosswind component was provided by a jet engine connected to a pipe that then splits to produce 3 crosswind jets spread over the 40m test track. This method of simulating the crosswind gust has meant that the test is a quick succession of 3 jets rather than a prolonged crosswind gust and could be seen in the results. As such the increased transient responses as seen in the present model tests can not be identified though a positive yaw rate was recorded at the gust exit. This would correspond to the minimum yawing moment peak identified during the current tests but insufficient data is available for a quantitative comparison. Maximum yaw rates were double that normally seen for conventional passenger vehicles and there was also increased lateral deviations.

9.3.2 Comparison with other Models in the Current Research

Aerodynamic force and moment data from the Range Rover model differ slightly in magnitude compared to that measured for the 2-box model although the trends are similar. The limited pressure data of the Range Rover model also compares well to that for the 2-box model.

A comparison of steady state force and moments for all 5 models is shown in Figure 9-13 to Figure 9-16. Comparing lift force coefficients first, it can be seen that 1-box type vehicles have an increased variation with yaw angle compared to 2-box type vehicles. The relatively lower values of the 2-box type are attributed to the positive pressure that acts on the windscreen, a component of which is negative lift. The radiused edged box gave the greatest variation of lift force coefficient between 0 and 25° yaw as well as the minimum and maximum lift force coefficients throughout the yaw angle range tested.

Side force coefficients differ little for all models tested with the exception of the flat plate values that are much higher. Figure 9-14 shows that the values of flat plate side force coefficients are lower but this is because flat plate side force coefficients are non-dimensionalised by side area instead of the frontal area that is used for other models. The increased peak pressures acting on the leeward face cause the larger side force of the flat plate model. In addition, this pressure force is concentrated at the leading edge and the maximum distance from the moment reference point.

There are considerable differences between the yawing moment coefficient for all models tested. Flat plate yawing moment coefficients are greatest (again shown lower but non-dimensionalised by side area and length) because large negative pressures occur at the leading edge. Radiused edged 1-box and Range Rover models have approximately equal values throughout the yaw

range tested but the 2-box model is comparatively lower. The sharp edged 1-box model is distinctly different from all others, as it is the only shape to attain a negative yawing moment for the yaw angle range tested. This is due to the lower peak pressures within the leeward separation bubble being balanced by the pressures acting on the rear of the leeward face (generated by the vortex originating from the top edge). Therefore, the resultant side force acts to the rear of the midpoint at low angles of yaw and only slightly forward at a yaw angle of 25°. For radiused edged bodies all pressures are intensified and the leeward separation bubble is the dominant component of the yawing moment coefficient.

Rolling moment coefficients show a linear decrease in values with increasing shape complexity. The sharp edged 1-box model has the highest value and the Range Rover model the lowest. All models display an approximate linear increase of rolling moment coefficient with increasing yaw. The leeward longitudinal vortex originating from the top face is the main component of the rolling moment coefficient. The pressures within the vortex are higher in radiused edged models resulting in a higher rolling moment on the leeward face. However, the components of rolling moment on the windward and top faces become negative when the edges are radiused and results in a consequent reduction in the rolling moment.

9.4 Conclusions

Results from the tests of the range rover model can be summarised as follows:

7. Steady state side force, yawing and rolling moment coefficients display an almost linear variation with increasing yaw up to 20°. Above this value the increase with yaw reduces up to 25° yaw.
8. Transient responses are noticeable in lift force and yawing moment

A comparison of the steady state aerodynamic force and moment coefficients for all models tested in this research has shown:

9. A flat plate model generates the highest side force but differences between 1-box and 2-box types are small
10. 1-Box type vehicles have greater lift force coefficients than 2-box type vehicles
11. Radiusing of edges increases the steady state yawing moment coefficient
12. Radiusing of edges decreases the steady state rolling moment coefficient

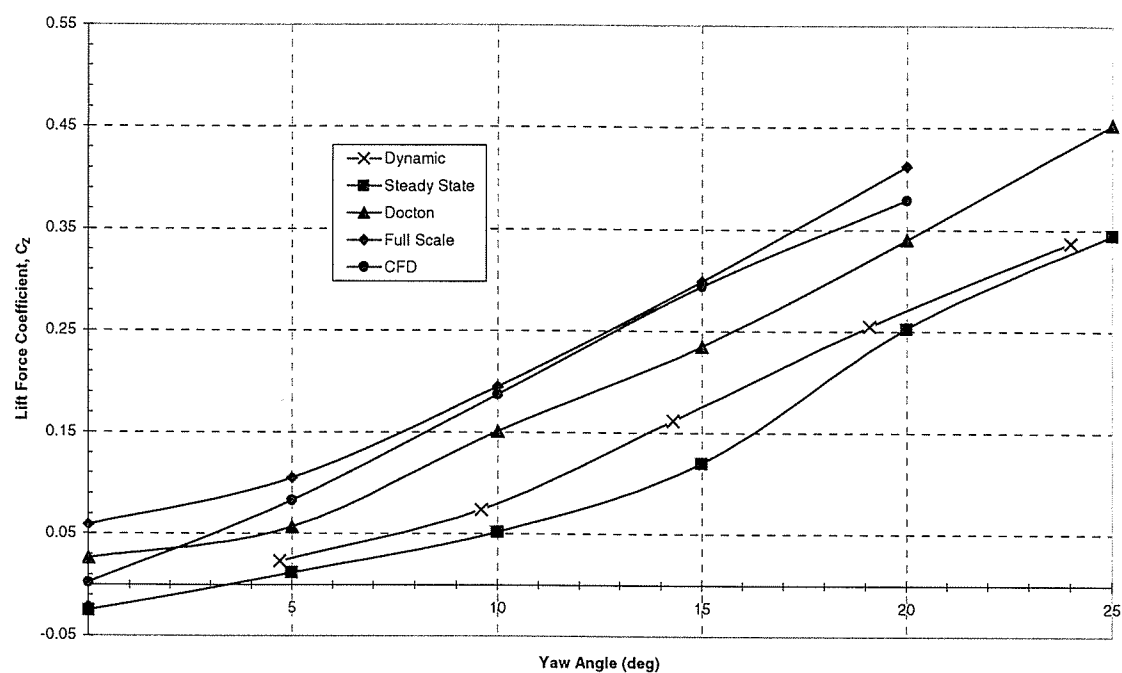


Figure 9-1 Variation of Lift Force Coefficient with Yaw Angle for Range Rover Model

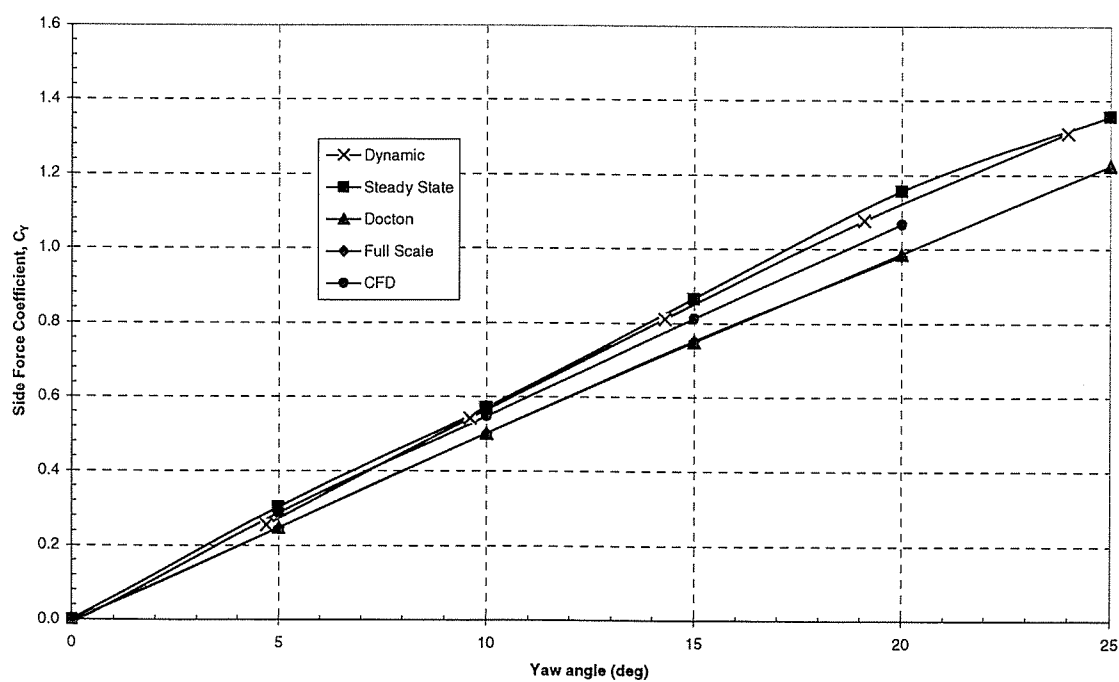


Figure 9-2 Variation of Side Force Coefficient with Yaw Angle for Range Rover Model

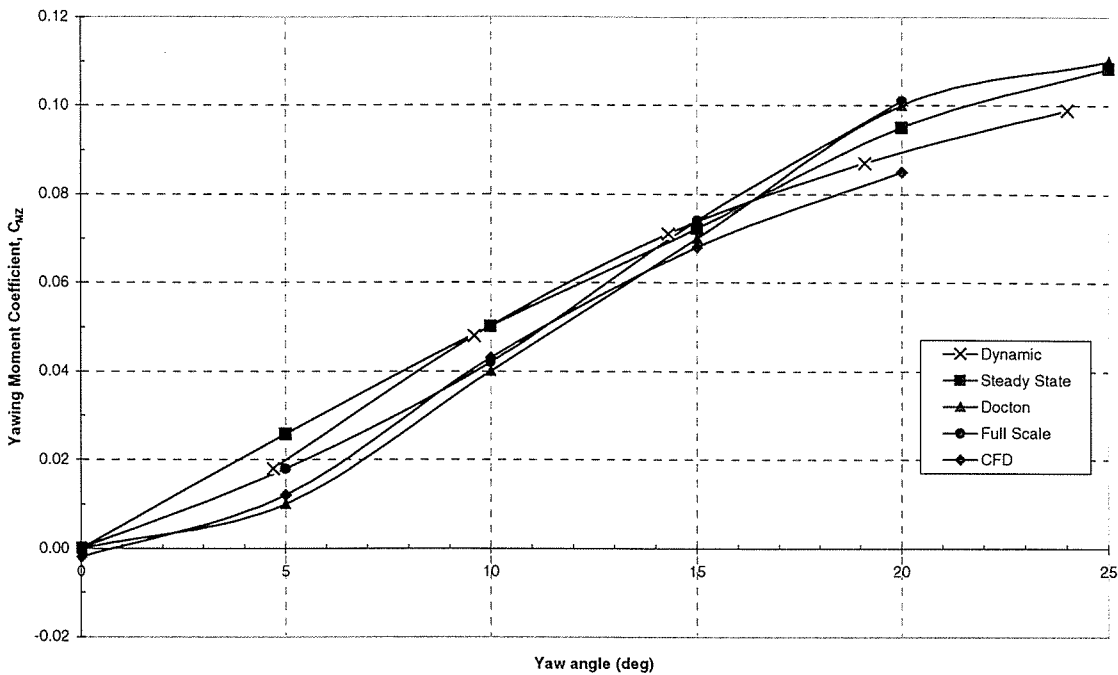


Figure 9-3 Variation of Yawing Moment Coefficient with Yaw Angle for Range Rover Model

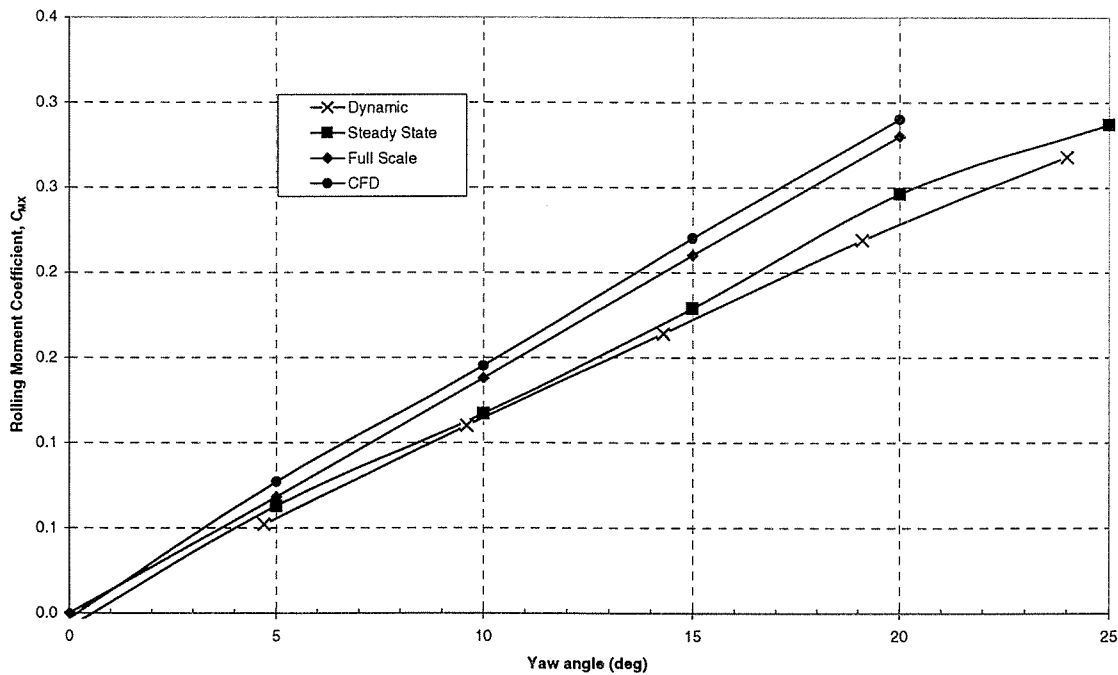


Figure 9-4 Variation of Rolling Moment Coefficient with Yaw Angle for Range Rover Model

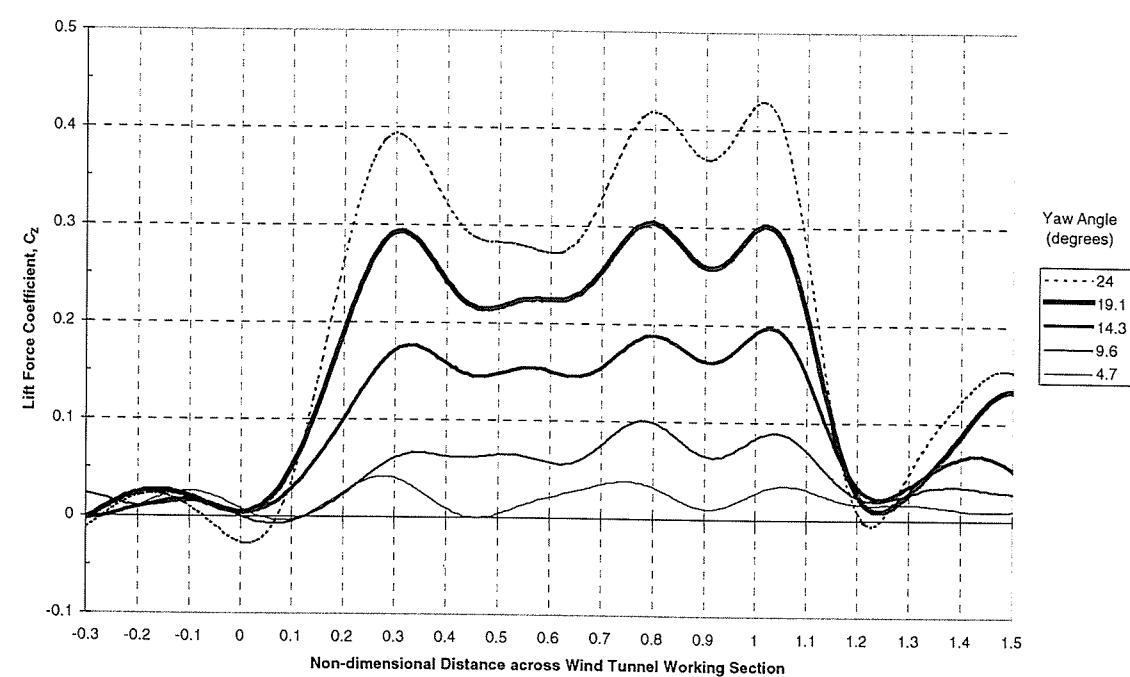


Figure 9-5 Range Rover Model Lift Force Coefficient Dynamic traces for 5 - 25° Yaw Angle

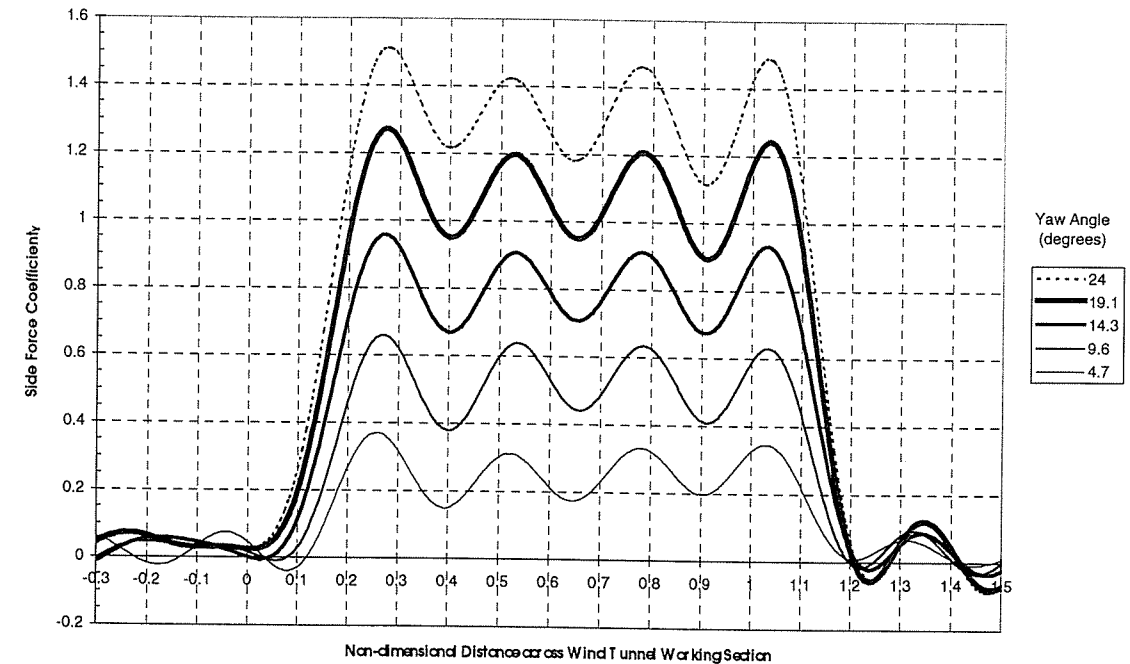


Figure 9-6 Range Rover Model Side Force Coefficient Dynamic traces for 5 - 25° Yaw Angle

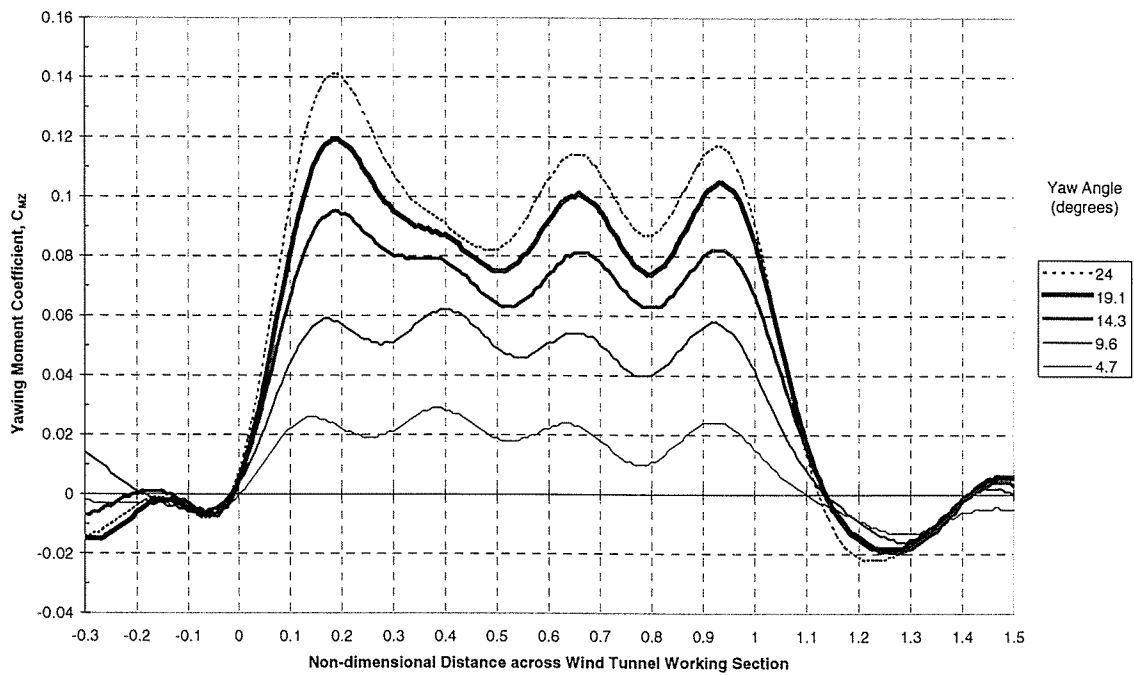


Figure 9-7 Range Rover Model Yawing Moment Coefficient Dynamic traces for 5 - 25° Yaw Angle

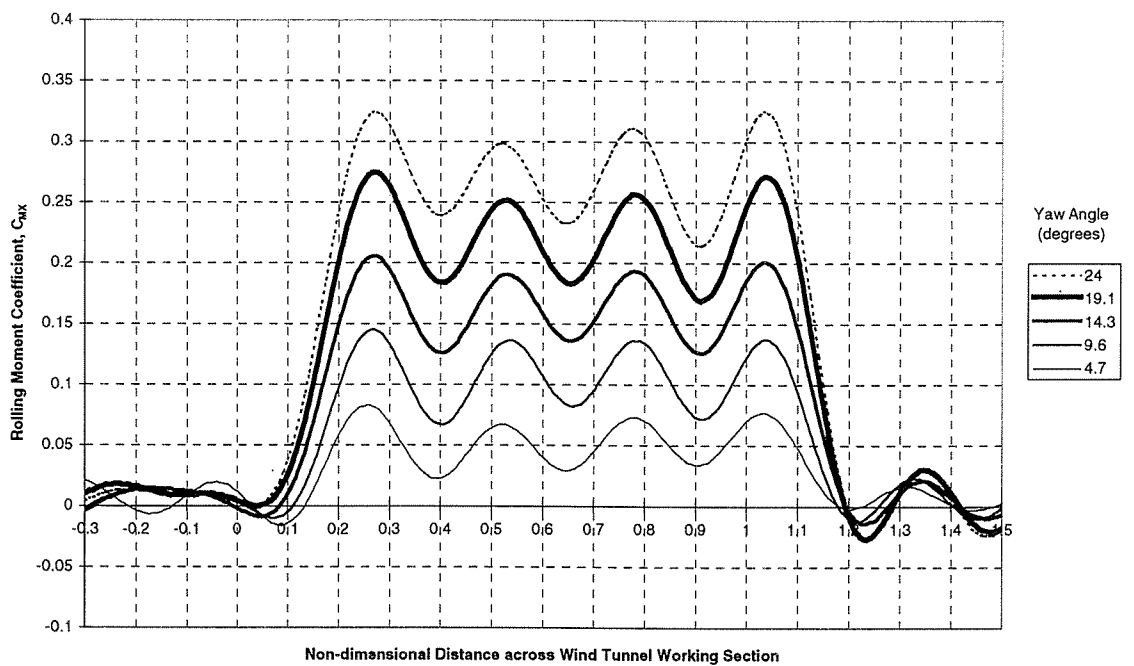


Figure 9-8 Range Rover Model Rolling Moment Coefficient Dynamic traces for 5 - 25° Yaw Angle

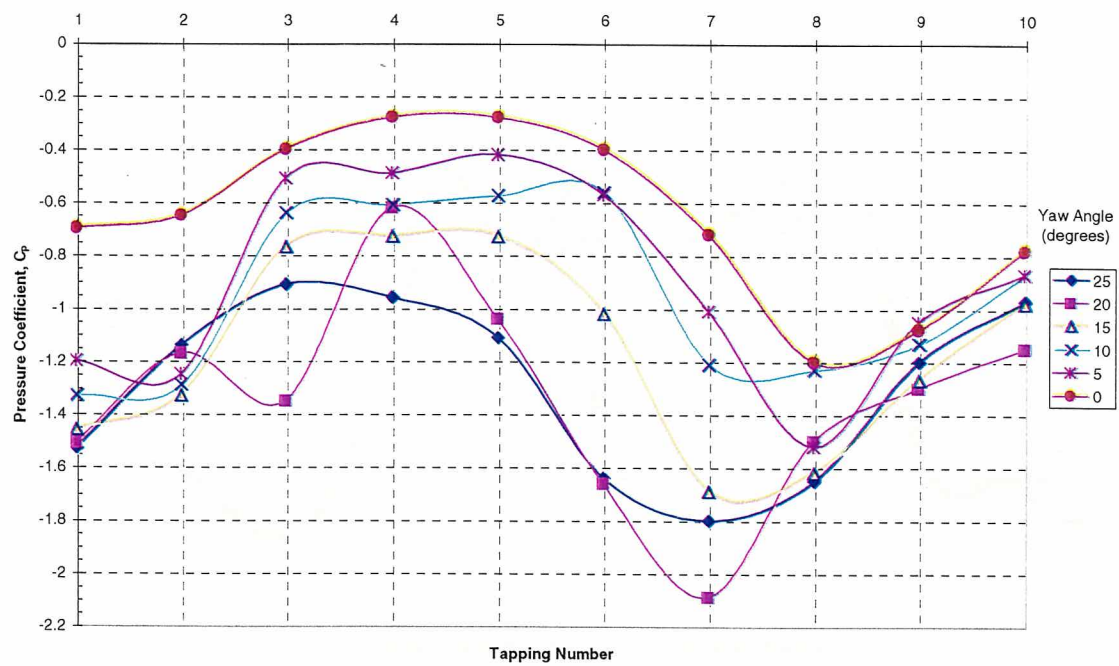


Figure 9-9 Range Rover Model Steady State Pressures 0 - 25° Yaw

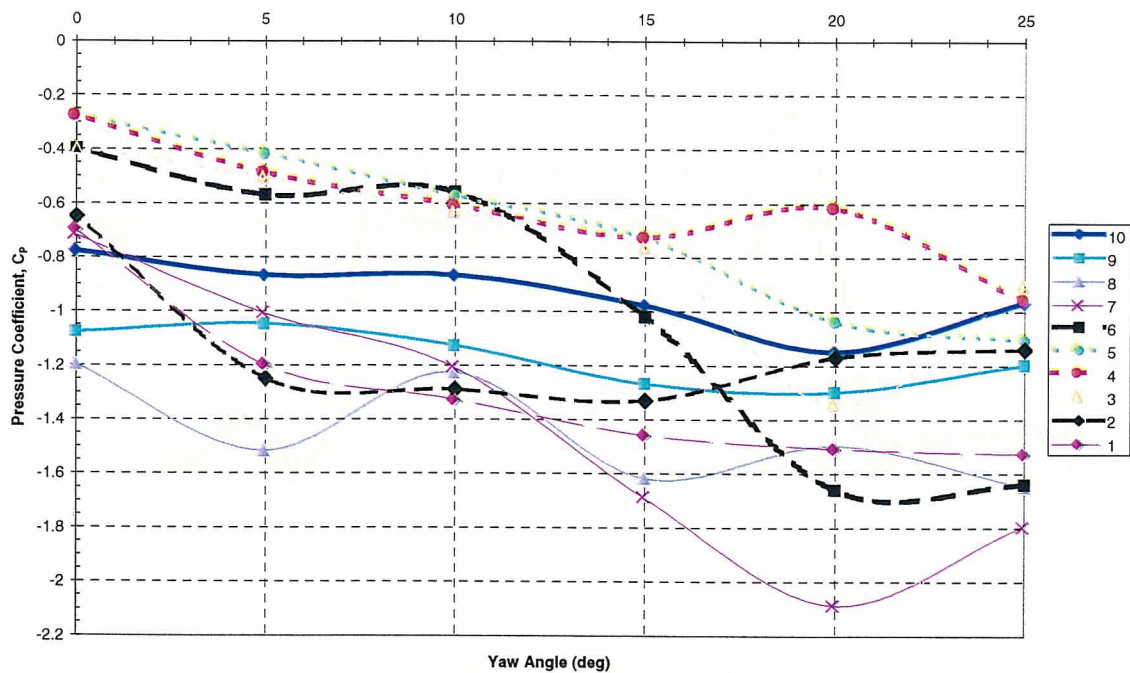


Figure 9-10 Range Rover Model Steady State Pressures, Tapping No. 1-10

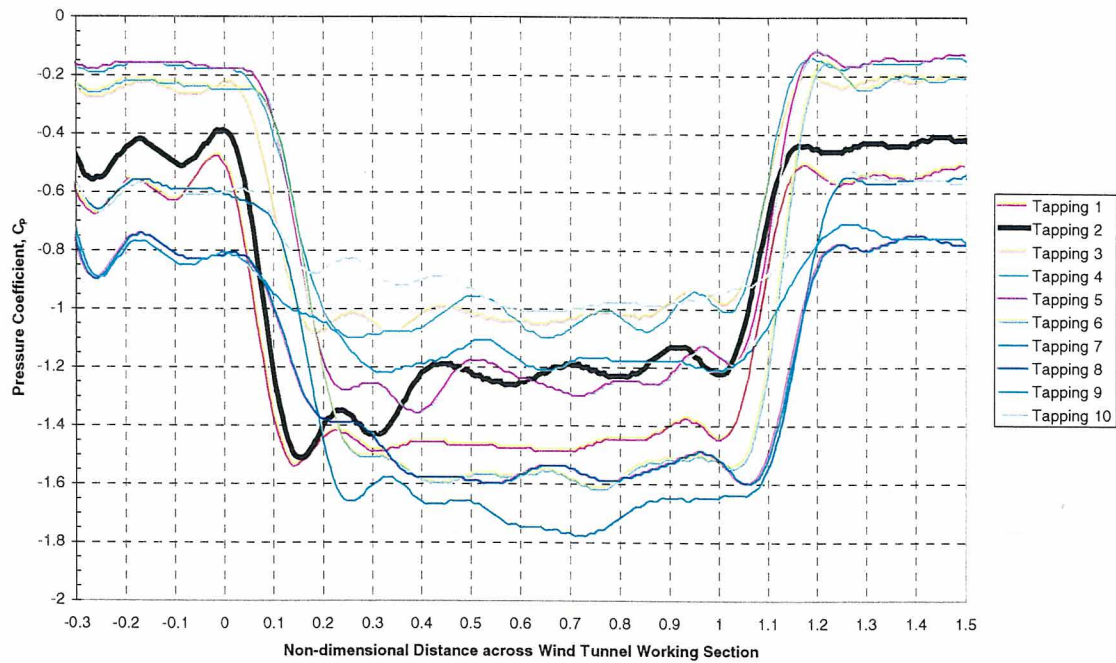


Figure 9-11 Range Rover Model Dynamic Pressures at 24° yaw, Tapping No. 1-10

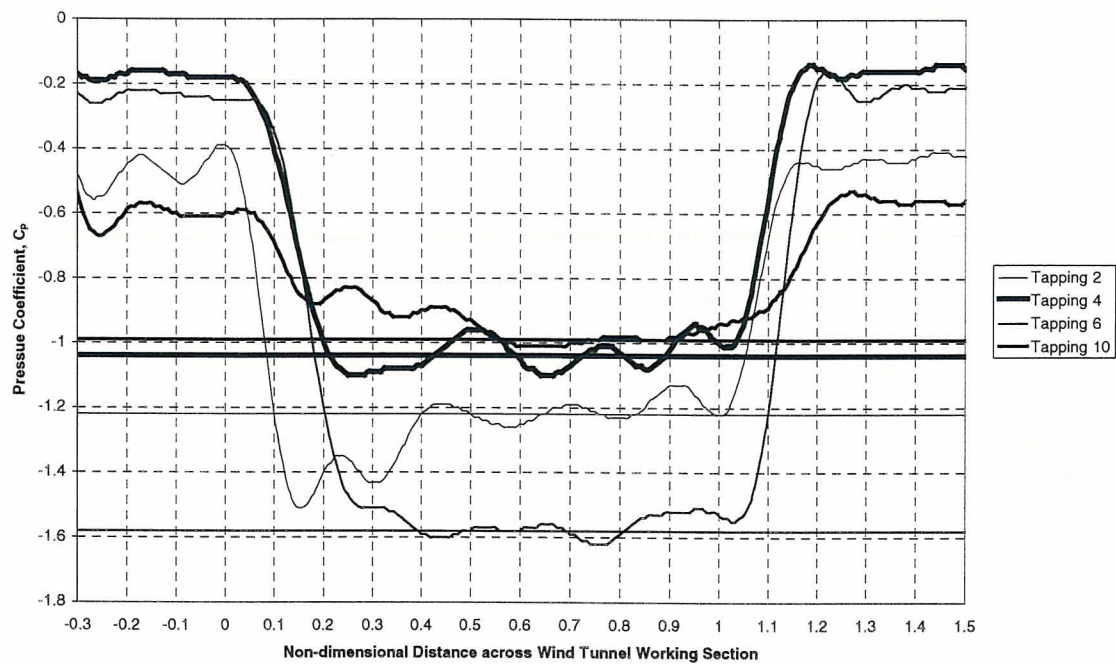


Figure 9-12 Comparison of Mean Dynamic and Steady State Pressure Coefficients

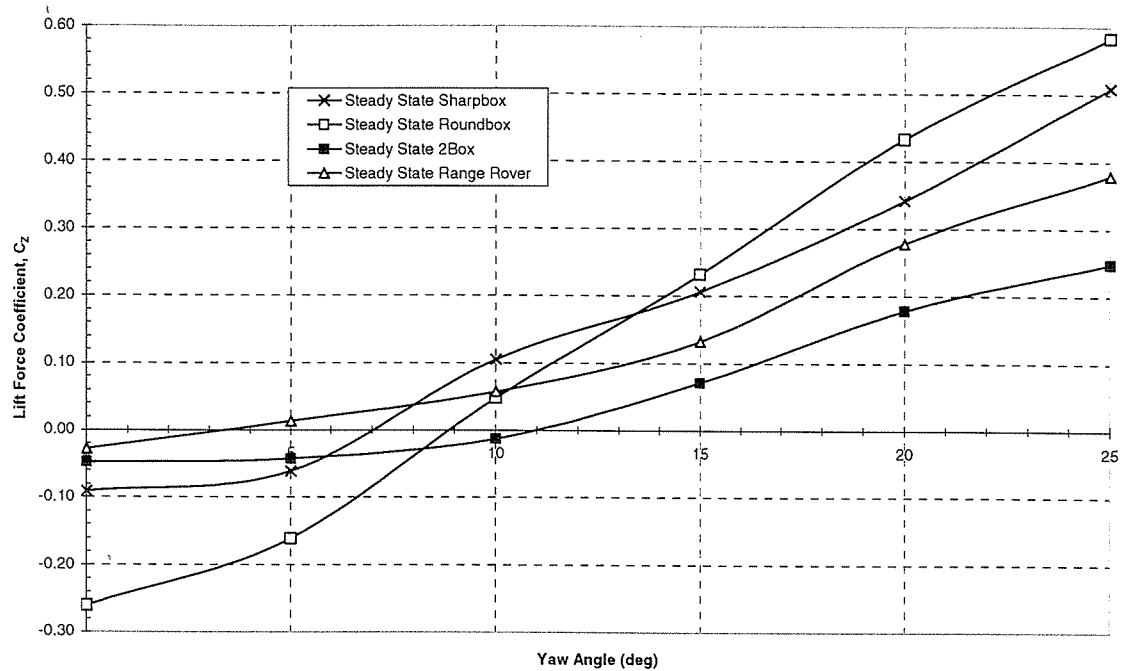


Figure 9-13 Comparison of Lift Force Coefficient for all Models

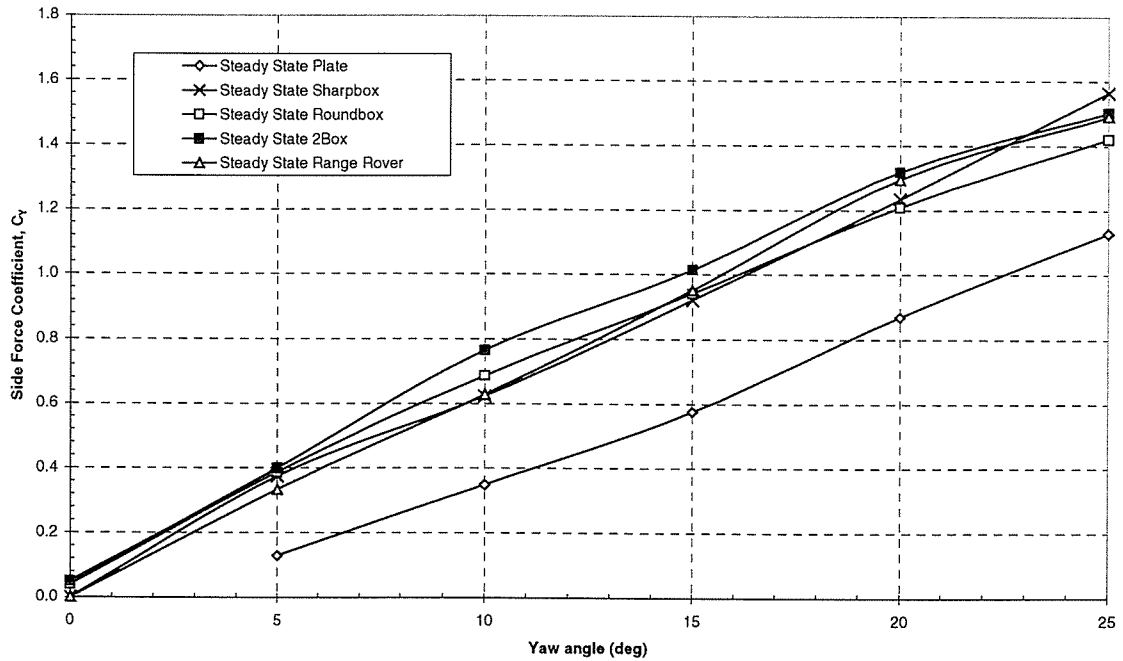


Figure 9-14 Comparison of Side Force Coefficient for all Models

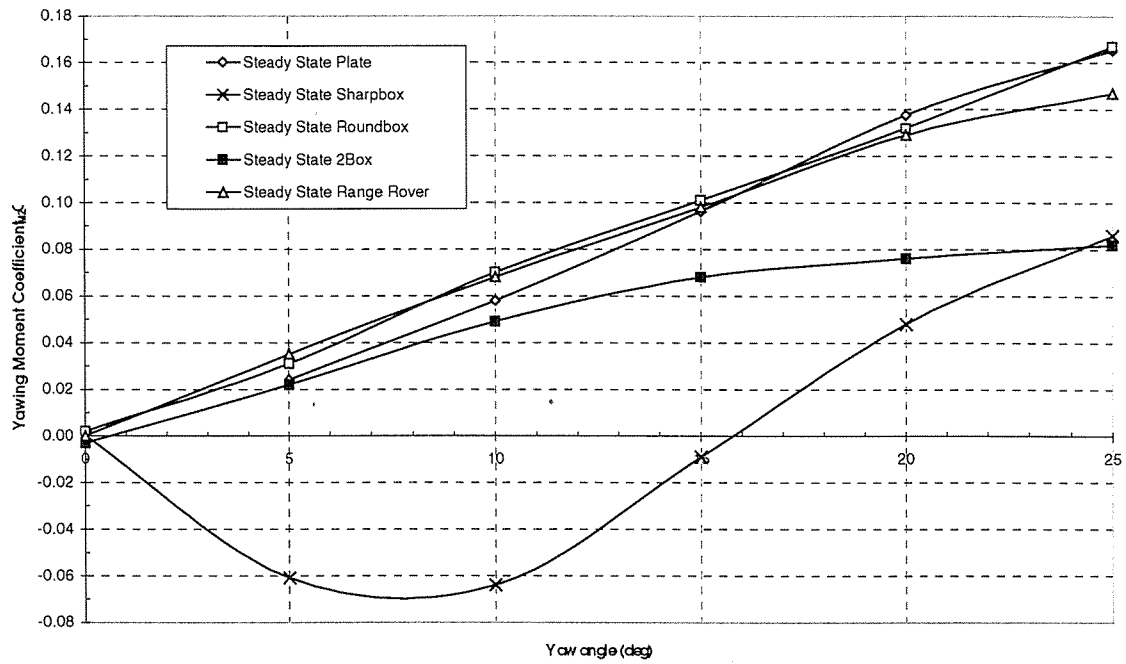


Figure 9-15 Comparison of Yawing Moment Coefficient for all Models

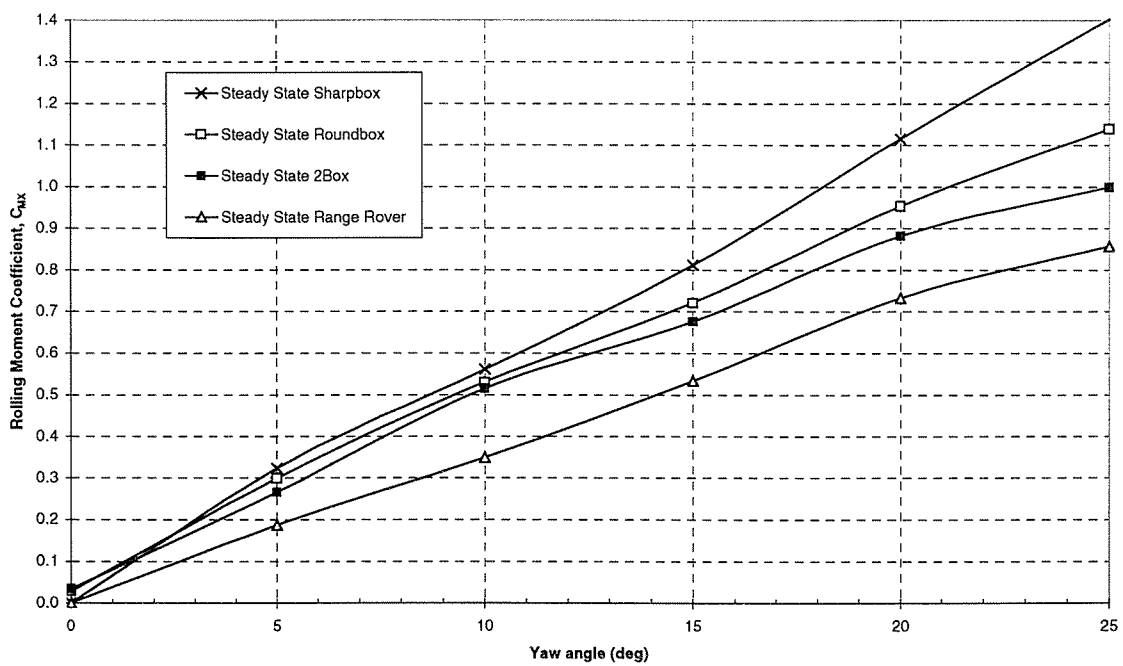


Figure 9-16 Comparison of Rolling Moment Coefficient for all Models

10. Summary and Conclusions

The aims of this research program were to:

1. Assess the crosswind sensitivity of sports utility vehicles in light of proposed environmental legislation limiting carbon dioxide emissions
2. Develop a remote pressure measurement system for use under dynamic testing conditions
3. Conduct a series of tests on simple geometric shapes resembling the aspect ratios of SUV's, to correlate pressure and aerodynamic force data and gain a greater understanding of SUV aerodynamics under transient crosswind conditions

10.1 Overall Summary of SUV Crosswind Sensitivity

Design features that distinguish a sports utility vehicle from other classes of passenger vehicle include, amongst others:

- Bluff bodied appearance
- Off-road capabilities results in a relatively high mass
- Large side area rearward of mid wheelbase

These features are seen to be a benefit with respect to crosswind sensitivity but even so, the SUV shows increased crosswind sensitivity when compared to a conventional passenger vehicle.

A literature survey of the impact of future environmental legislation concerning greenhouse gas emissions found that environmental legislation will force an improvement to the fuel efficiency of cars. This will cause:

- Vehicles to become lighter and so decrease tyre reactions
- Vehicles to have a lower drag coefficient

A decrease in tyre reactions from reduced mass means that the crosswind sensitivity would be increased. Sports utility vehicles that previously relied upon their mass to counteract instabilities in crosswinds would be particularly affected.

Methods to reduce the drag coefficient from specific shape changes have been found to be in conflict with reduction of the yawing moment. Any change to reduce the drag coefficient of the sports utility vehicle would then increase its already high crosswind sensitivity.

10.2 Development of a Dynamic Pressure Measurement System

In assessing crosswind aerodynamics, it was found that pressure mapping of the model surface is a better method of determining flow characteristics than by force data collection alone. Chapter 4 described the development of the pressure measurement system used in this research. Pressure measurement under the dynamic testing conditions of the Cranfield crosswind facility differs from conventional pressure measurement in that:

- Inertial effects become important
- A remote reference to the pressure transducer is needed
- Connecting tubing alters the frequency response of the system

A series of tests to determine the suitability of the selected pressure transducer found that it would give accurate and repeatable results. A method to adjust the frequency response of connecting tubing has also been devised and incorporated into subsequent data reduction.

The dynamic pressure contour maps are presented as animations also developed in this research. Individual pressures are initially calibrated and interpolated in Matlab programs to produce pressure contour maps of individual body faces for each time increment. A Fortran program then collated all the body faces to give the entire pressure surface for each time increment and outputted data in a format compatible with Fieldview CFD post processing software. Fieldview was then used to produce animations of the models and output in standard mpeg format.

10.3 Summary of Test Data

10.3.1 Concerning the Test Method

Despite improvements made to the test equipment, aerodynamic force data recorded during dynamic testing is still corrupted by noise. Integration of pressures to give dynamic force and moment changes is a better method of force measurement than by conventional balance. Pressure measurement does not suffer from signal noise contamination, however the accuracy is limited by pressure grid size.

The steady state condition is not established during the time that it takes to traverse the crosswind gust. This is a distance of 5 body lengths and is in agreement with previous research that suggests 7 body lengths are needed. A reduction in body size to amend this inaccuracy in simulation would decrease the Reynolds number.

Recorded aerodynamic coefficients were found to be Reynolds number independent between 1×10^5 and 3×10^5 , based on body width. All tests are conducted at a Reynolds number in the subcritical regime (1.8×10^5) but previous research suggests that the results can not be extrapolated to full-scale

vehicles that operate in the transcritical regime. This was found to be especially so for pitching moment and yawing moment coefficients.

10.3.2 Crosswind Sensitivity of Differing Vehicle Shapes

For the 1-box type model, the steady state flow structure at 0° yaw is characterised by long separation bubbles from all 4 longitudinal edges. With increasing yaw, the leeward face exhibits an increase of separation bubble length and magnitude of peak pressures together with the development of longitudinal vortices along upper and lower edges. This is coincident with skewing of the top face separation bubble towards the leeward face.

Dynamic testing of the sharp box model produced peaks in yawing moment approximately 2.5 times greater than observed for the steady state condition. The yawing moment peak on gust entrance can be explained by a combination of:

- collapse of the windward separation bubble
- negative pressures in the leeward leading edge separation bubble causing an increased yawing moment before the flow has established itself over the rear half.

The peak in the leeward face yawing moment as the model exits the gust is due entirely to the collapse of the leeward separation bubble to a point located towards mid axis and the upper edge. The mechanism of leeward vortex collapse is seen to be interactive with the flow structure on the top face. Radiusing of all edges of a 1-box type model found that:

- For the steady state condition all aerodynamic coefficients are reduced with the exception of yawing moment, due to increased pressures within the leeward face leading edge separation bubble
- In dynamic tests, the peak on gust entrance remains the same as the sharp edged case but the peak on exiting is reduced because the point of action of the moment has moved towards mid-axis. Gust entrance peaks were approximately 1.5 times greater than the steady state value.

A comparison of the crosswind sensitivity of 1-box and 2-box shapes found that:

- Steady state 2-box yawing moment coefficients are lower than the 1-box because of a greater side area rearward of mid axis
- Maximum yawing moments at gust entrance and exit for the 2-box model are not as great as that seen on a 1-box type model
- The windscreen face of the 2-box model shows significant transient activity.

10.3.3 Applications to Crosswind Sensitivity Assessment

It has previously been noted by many researchers that the transient response is greater than the steady state and that the maximum peak at a gust entrance should be accounted for in an assessment of a vehicle's crosswind sensitivity.

This research has shown that a minimum peak also occurs as a vehicle exits a crosswind gust. Rather than consider the maximum yawing moment reached when a vehicle is subjected to a crosswind, perhaps a better assessment would be the difference between the maximum and minimum values of yawing moment, since it is the magnitude of yawing moment change that determines the yaw rate response when a vehicle is subjected to a crosswind and which has the greatest influence on a driver's perception of vehicle crosswind sensitivity.

Many researchers have reported that radiusing of the leading edge is detrimental to the yawing moment because the modification prevents separation of the boundary layer and therefore permits large negative pressures to act in this area. The present research has also shown the steady state yawing moment to be increased when the edges are radiused. However, this research has shown that radiusing reduces the minimum peak in yawing moment at the gust exit. Therefore it could be said that the difference between maximum and minimum peaks are reduced by edge radiusing and that the crosswind sensitivity of radiused edged bodies is better than the sharp edged case.

10.4 Further Work

10.4.1 Test Facility Improvements

For an improved Reynolds number simulation, the test facility would require adaptation for bigger models and higher test speeds. The testing of models at higher test speeds would also increase the accuracy of measured pressures. A move towards bigger models would require an increase in the length of the crosswind gust so that a steady state condition is achieved in the time taken to pass the gust.

Sensor Technics SLP010DD4 pressure transducers suited the purpose of this research because it was unsure what the effects of the dynamic loading would be. The transducers were inexpensive and tests showed them to give reliable data. Repeatability and accuracy of measured pressures could be further improved by a future upgrade to pressure transducers that are temperature compensated and calibrated.

To eliminate mechanical noise from the force and moment dynamic data a redesign of the force balance is needed. Previous efforts have been aimed at reducing the noise entering the system whereas it would be better to concentrate on altering the frequency response of the balance so that unwanted noise is not recorded.

Several model materials have been used in this research in an attempt to provide optimum stiffness and minimum weight. Stiffness of the model is needed to give accurate and repeatable results and weight reduction decreases the magnitude of unwanted noise in dynamic tests. Foam board with additional balsa wood stiffeners was used for the 1-box models. The models were lightweight and so gave minimal signal noise but stiffness and hence repeatability deteriorated over time. The 2-box model was initially made of

carbon fibre and gave best repeatability of force data. However, the model was double the weight of the foam board models and oscillations were such that it was hard to determine what was noise and what was aerodynamic data. The final model construction was from solid foam hollowed out to reduce mass and gave the best performance.

The averaging technique of 3 runs for dynamic data was found to be insufficient when testing the 2-box model because the flow field was very unsteady. An average of 5, 10 or more would significantly improve accuracy. In which case, the test facility requires a system that can perform multiple pressure measurements without being labour intensive, an example being dynamic pressure measurements for the 2-box model. At present, there are 5 transducers recording a total of 228 pressure tapings over an average of 3 runs. This requires 135 runs for each yaw angle tested and not including repeat measurements to ensure confidence in the data. The pressure tapings are individual tubing's and must be connected to the transducers by hand, which required opening up the model and then resealing every 3 runs. A scanivalve system would help in this respect but would also increase the mass of the model.

The present firing mechanism of the model carriage is eccentric to the drag axis, therefore pitching moment data was very erratic because firing the model incurred an initial oscillation. This could be solved by moving the point of application of the propulsion force towards the moment centre.

New data acquisition software needs to be implemented. Present data acquisition saves the data with a filename equal to the time at which it was recorded and hence data could only be stored once every minute. Additionally the program did not save the data as a readily usable file and further processing was needed to convert data to the useable comma separated variable file type.

A dynamic flow visualisation system still needs to be developed. Stills during dynamic tests have previously been taken by Macklin³ but this doesn't show what happens to the transient flow field at gust entrance and exit. An attempt was also made during this research to use a high-speed camera and fluorescent tufts on the models but was not completed because of insufficient time. It is felt that dynamic flow visualisation would be an invaluable tool in understanding the change in separation bubbles and vortices at the gust entrance and exit.

10.4.2 Transient Crosswind Research

This research has concentrated only on the overall shape of vehicles and there is much scope for further research on individual shape changes that have been previously investigated in the steady state. These include the angle of windscreen inclination, plan view tapering and the effect of front spoilers. Other questions that remain unanswered include:

- What are the effects of rotating wheels?
- How do the inclusion of radiator flows affect the transient response?

Appendix A: Comparison of Previously Collected Data

A series of tests was conducted to see what effects the implemented track improvements had upon aerodynamic data. Tests with the squareback model as used by Macklin³ with no freestream turbulence generation and with the groundboard in place were chosen for comparison. Three data sets of an average of 3 runs per 5° yaw angle increment from 0 to 45° were recorded.

Differences in Test Technique

Apart from the implemented track improvements, there were several notable differences between the data collection method used by Macklin³ and the present research. Firstly in the current research, the wind tunnel freestream dynamic pressure was recorded from a Pitot tube located in the working section whereas Macklin³ used the wind tunnel static rings to calculate freestream dynamic pressure. The wind tunnel static pressure was found to vary with distance downwind of the wind tunnel and therefore freestream dynamic pressure and tunnel velocity would be in a small error when calculated by the static rings.

A further difference in test technique between the current study and the work of Macklin³ was in calibrating the balance. Previously the 5-component balance was calibrated in lift and side force at either axle as well as rolling moment. From the calibration matrix, the values of lift, pitch, yaw and side force could then be calculated. Because drag is not measured, Macklin³ considered this method because the position of the x-axis moment centre is undefined and could introduce errors when calibrating in lift and pitch alone. However when calibrating, the live ends of the balance are connected by the model and therefore any load applied to the front axle would also affect the rear axle component depending on model stiffness. The squareback model as used by Macklin³ deteriorated over time and consequently the model stiffness would have changed resulting in calibration errors. The present calibration method calibrates the balance in front and rear lift, side force, yaw and roll and the values of lift, pitch and side force at front and rear axles are then calculated. Macklin³ claimed that previous calibrations gave results to within 2% of the applied load.

An average of accuracy's as a percentage error for 3 present calibrations are shown in Table A-1. It can be seen that the errors in roll and yaw are considerably higher than seen by Macklin³. The reasons for this increased error can be attributed to model deformation and deterioration.

Table A-1 Balance Calibration Errors

Force/Moment	Lift	Pitch	Side	Yaw	Roll
Error (%)	1.3	1.1	0.9	3.4	6.7

Data Accuracy and Repeatability

Table B-2 shows the standard deviation of the mean coefficients taken from 3 runs at 20° yaw expressed as a coefficient and compared with data obtained by Macklin³ for 9 runs at 17° yaw. It can be seen that the repeatability within a dataset has been significantly improved with the exception of the yawing moment coefficient. However, the deviation is still slight and represents an error of only 2%.

Figure A-1 compares repeatability between datasets obtained by Macklin³ over the course of his test program and the three datasets collected in the current study. The table shows standard deviations for the 15° yaw case expressed as a coefficient and also as a percentage. It can be seen that present repeatability is improved with the exception of the front lift coefficient but overall the repeatability between datasets is still unsatisfactory.

The reason why the datasets in the current study vary to this extent when considering that data collection was relatively close together is because the track bearing positions were altered between tests. This confirms initial findings that the adjustment of the bearings is critical in obtaining satisfactory repeatability. Bearing gap clearance is now closely monitored and accurately adjusted to between 0 and 0.05mm for subsequent tests.

Table B-2 Repeatability between Datasets

Coefficient	Macklin ³	Current Study
C_{LF}	0.012 (7.6%)	0.026 (21.3%)
C_{LR}	0.014 (14.5%)	0.015 (13.5%)
C_S	0.041 (6.2%)	0.008 (0.9%)
C_Y	0.007 (13.6%)	0.010 (6.9%)
C_R	0.012 (11.6%)	0.023 (10.9%)

Results and Discussion

Figure A-3 to A-7 show mean aerodynamic coefficients for 0 to 40° yaw for three datasets recorded after measures to improve track repeatability had been implemented. The mean of the three datasets is shown as well as data recorded by Macklin³ for the squareback configuration with the groundboard in place and no boundary layer generation.

The front lift, side force and yawing moment coefficients obtained in the current study and those of Macklin³ correlate well but there are considerably discrepancies between the rear lift and roll coefficients. The first point to consider is that because of the track signature subtraction in the data reduction, the results of Macklin³ are relative to the zero yaw coefficient. The figure implies that at zero yaw there is zero front lift when in fact zero rear lift occurs at approximately 15° yaw. When comparing the mean rear lift coefficient of the 3

datasets to steady state values recorded by Macklin³ (Figure A-2) the results are more favorable though only at higher angles of yaw. A further point noted by Macklin³ from visualisation of the flow is that the dynamic values of rear lift and roll coefficient are based on a mean value and do not reflect a steady flow condition over the rear of the model.

Macklin³ used the method of continuity to correct for the change in freestream velocity due to blockage but it is unclear in the data reduction program if this was applied to the presented data. No blockage correction was applied to the data recorded in the current study but for all yaw angles the increase in freestream velocity due to blockage was never greater than 2.6%.

Several modifications to the track equipment have been completed since Macklin³ tested. The squareback model has been damaged and repaired several times and the moving apparatus has undergone a major overhaul including new mounting brackets and containers and a completely different firing mechanism. This has led to a great reduction in mass and consequently the natural frequencies of individual track components will have changed. The finite element frequency analysis as carried out by Macklin³ showed there to be an oscillation in roll at 25Hz. Track improvements and model deterioration would certainly have changed this frequency and could alter the mean aerodynamic roll coefficient. Unfortunately, the model as tested would be difficult to model in a finite element analysis because of the uncertainty of node and member stiffness.

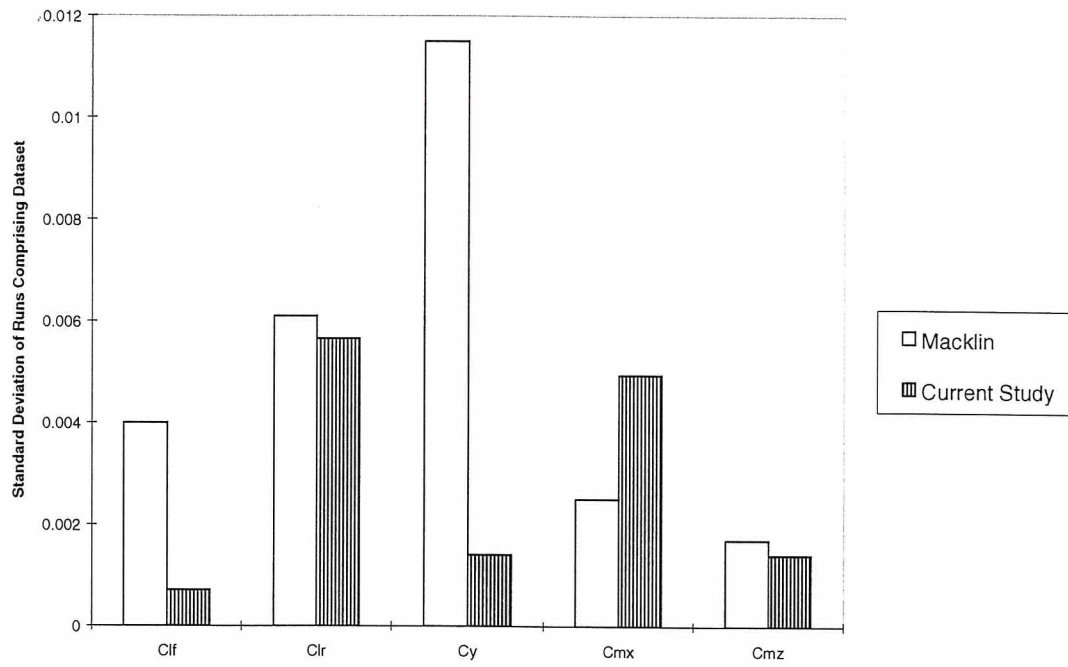


Figure A-1 Repeatability within a Dataset

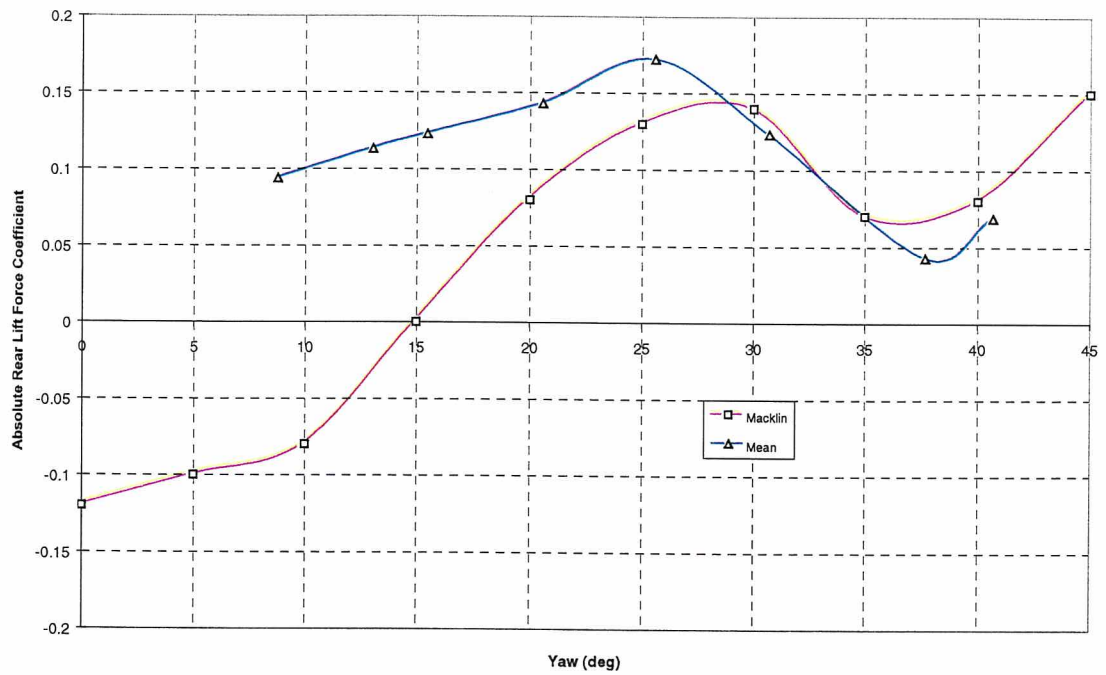


Figure A-2 Comparison of Rear lift Coefficient for Passenger car Model

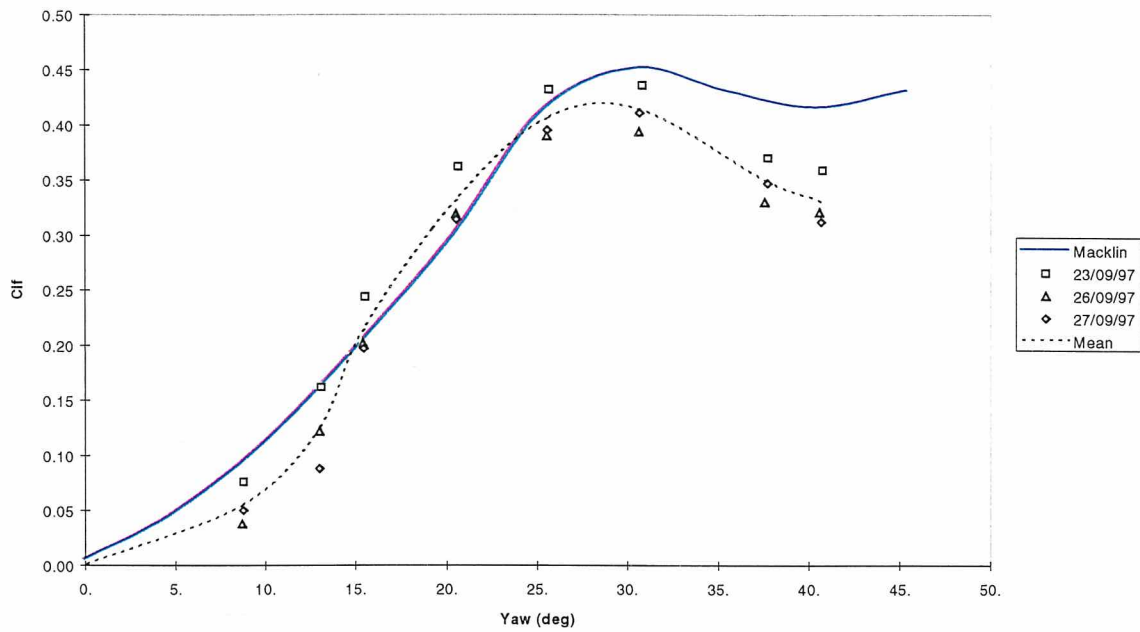


Figure A-3 Comparison of Front Lift Coefficient for Passenger car Model

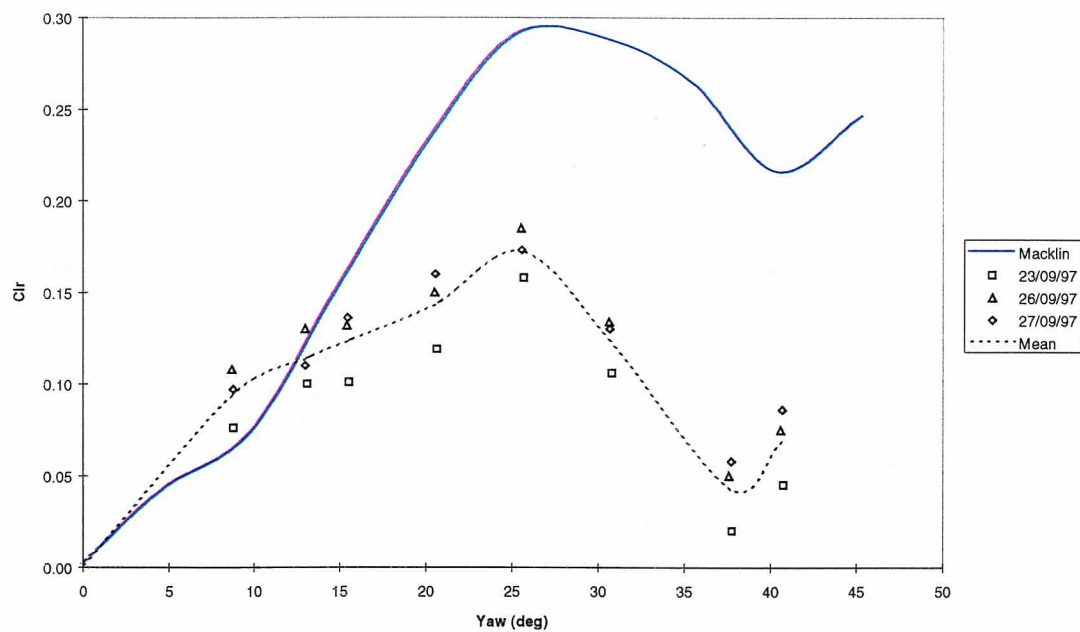


Figure A-4 Comparison of Rear Lift Coefficient for Passenger car Model

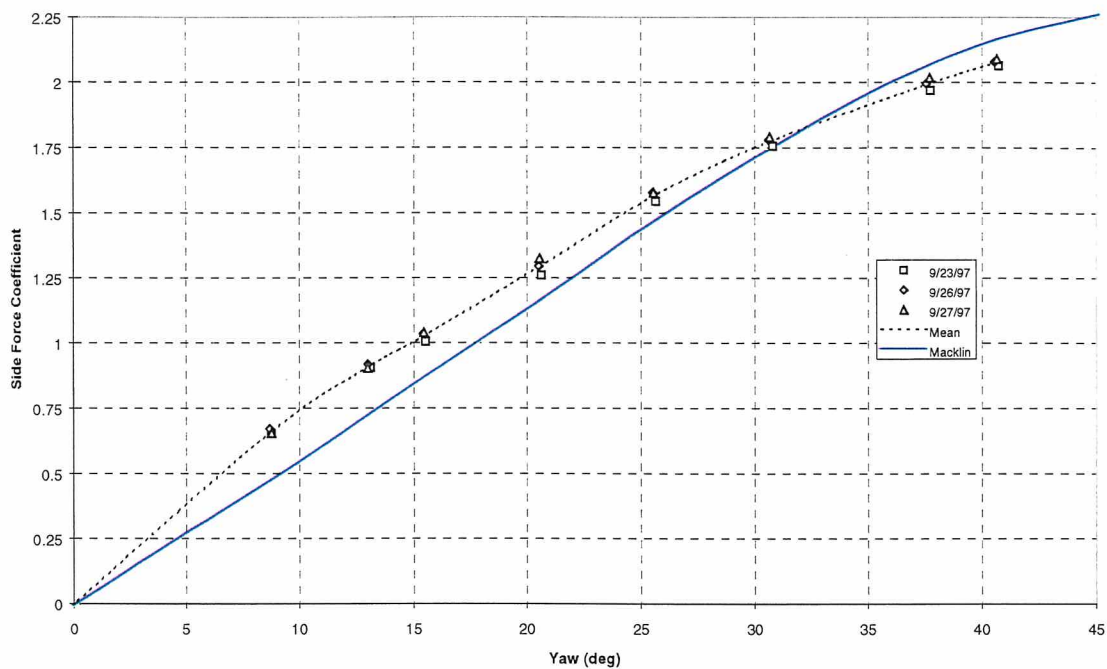


Figure A-5 Comparison of Side Force Coefficient for Passenger car Model

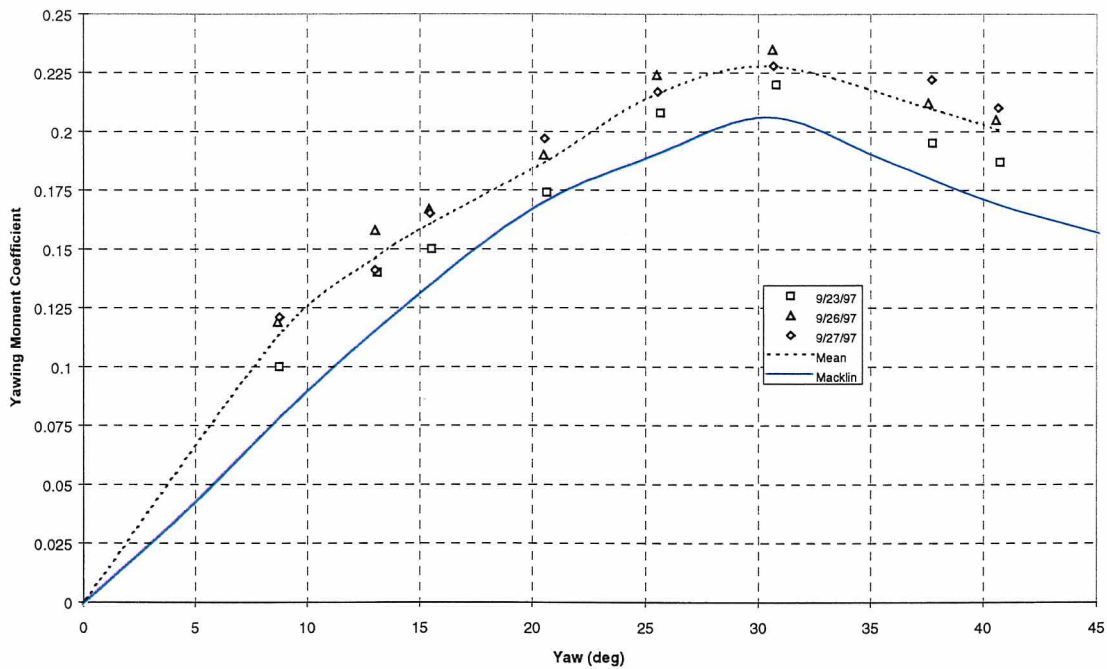


Figure A-6 Comparison of Yawing Moment Coefficient for Passenger car Model

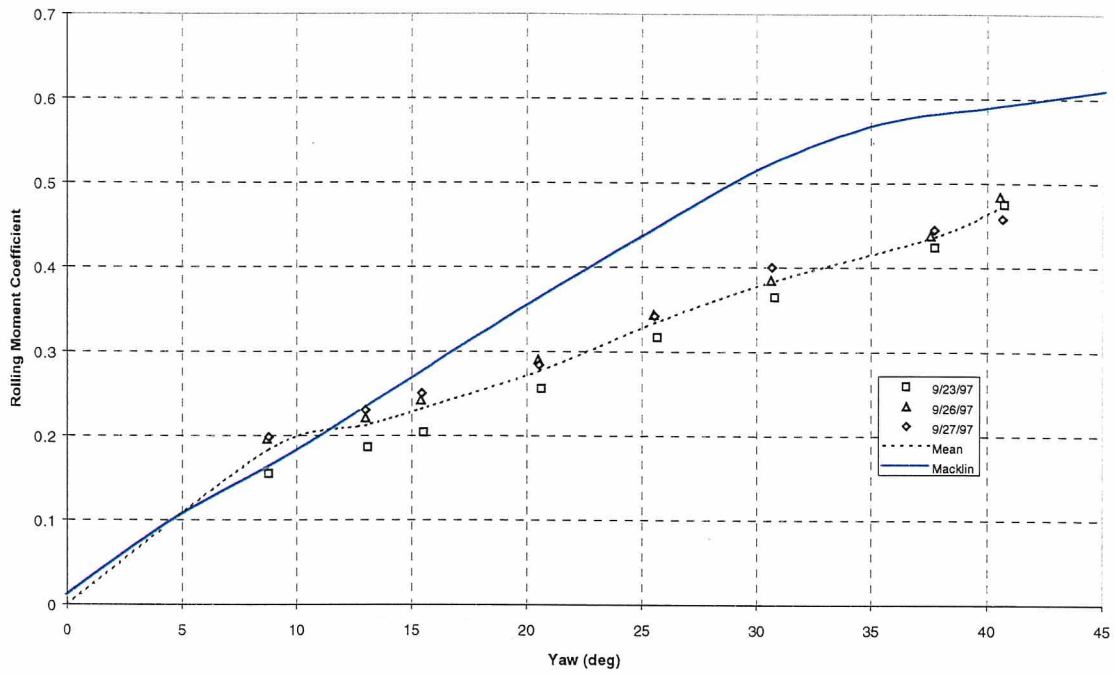


Figure A-7 Comparison of Rolling Moment Coefficient for Passenger car Model

Appendix B: Equipment Specifications and Calibrations

Force and Moment Data

All force and moment data was recorded using a purpose built strain gauged balance. Calibration was performed using a calibration cage located at the side of the crosswind track so that calibrations can be performed on the model itself. This was deemed necessary because of the interaction of body stiffness on the strain gauge elements at the front and rear of the balance. The balance was then calibrated in lift, pitch, side force, yaw and roll by applying check weights of 0.1kg to 4 calibration points located on the balance centre line and a distance of 0.2m between. A sample calibration is shown in Figure B-1.

Pressure Data

Calibration of all pressure transducers was done using a Druck pressure transducer calibrator. The Sensor Technics SLP010DD4 transducers were calibrated between 1 and -3 mbar and a typical calibration is shown in Figure B-2.

Specifications of Sensor Technics SLP010DD4 Pressure Transducer

Characteristics	Min.	Typical	Max.	Unit
Operating Pressure	-10	-	10	In. H ₂ O
Sensitivity $T_A=25^{\circ}\text{C}$	0.4	0.85	1.6	MV/V/In. H ₂ O
Full Scale Span 4 in. H ₂ O	20	40	80	MV
Temperature Coefficient of Span	-2500	-2100	-1700	Ppm/ $^{\circ}\text{C}$
Combined Linearity and Hysteresis	-	0.5	± 1.0	%FS
Long Term Stability	-	0.5	-	%FS
Response Time (10% to 90%)	-	1	-	Ms
Temperature Coefficient of Resistance	2800	3100	3400	Ppm/ $^{\circ}\text{C}$
Repeatability	-	0.5	-	%FS
Position Sensitivity	-	5	-	MV/V/g

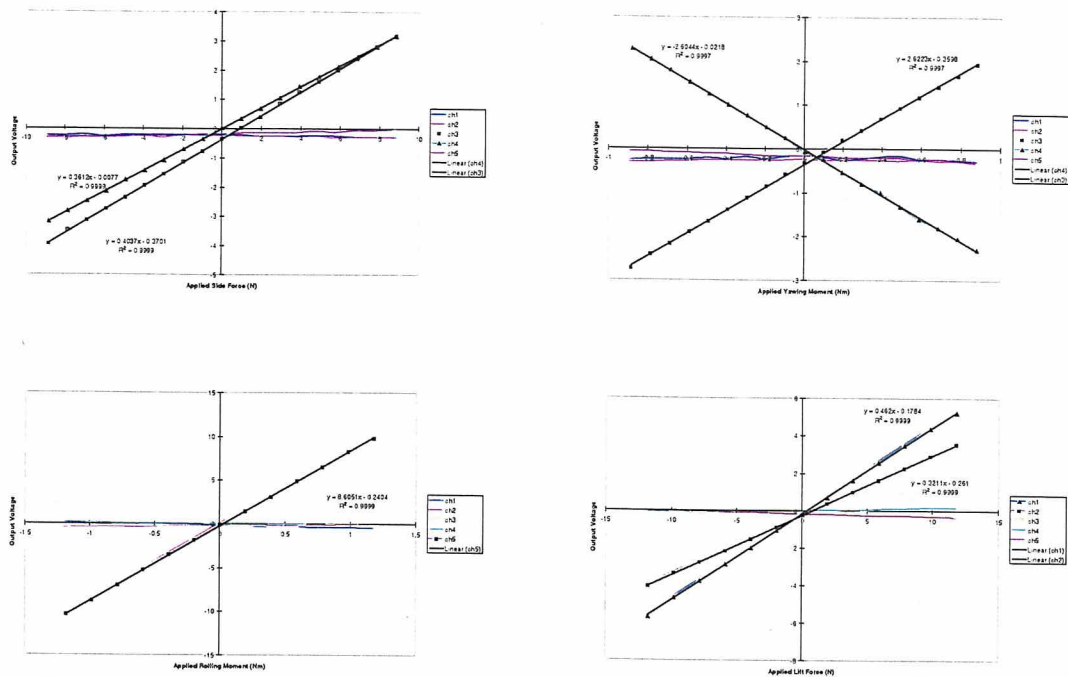


Figure B-1 Typical Balance Calibration

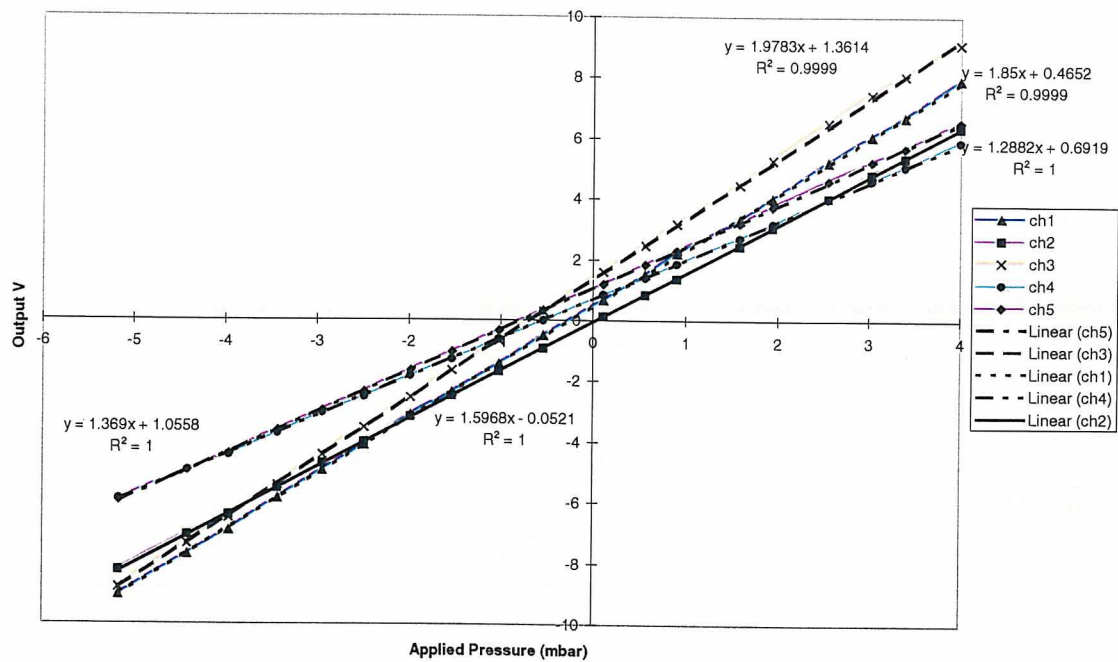
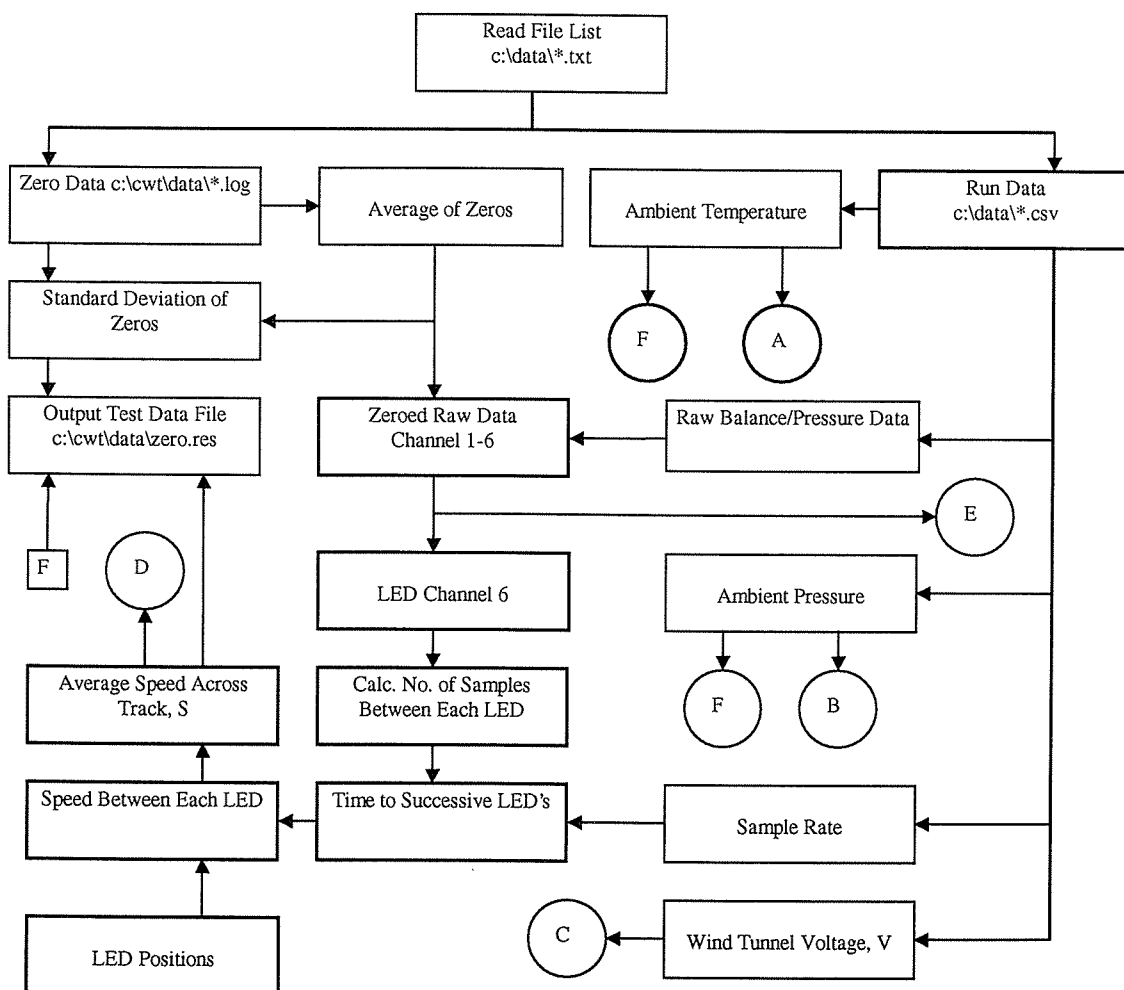
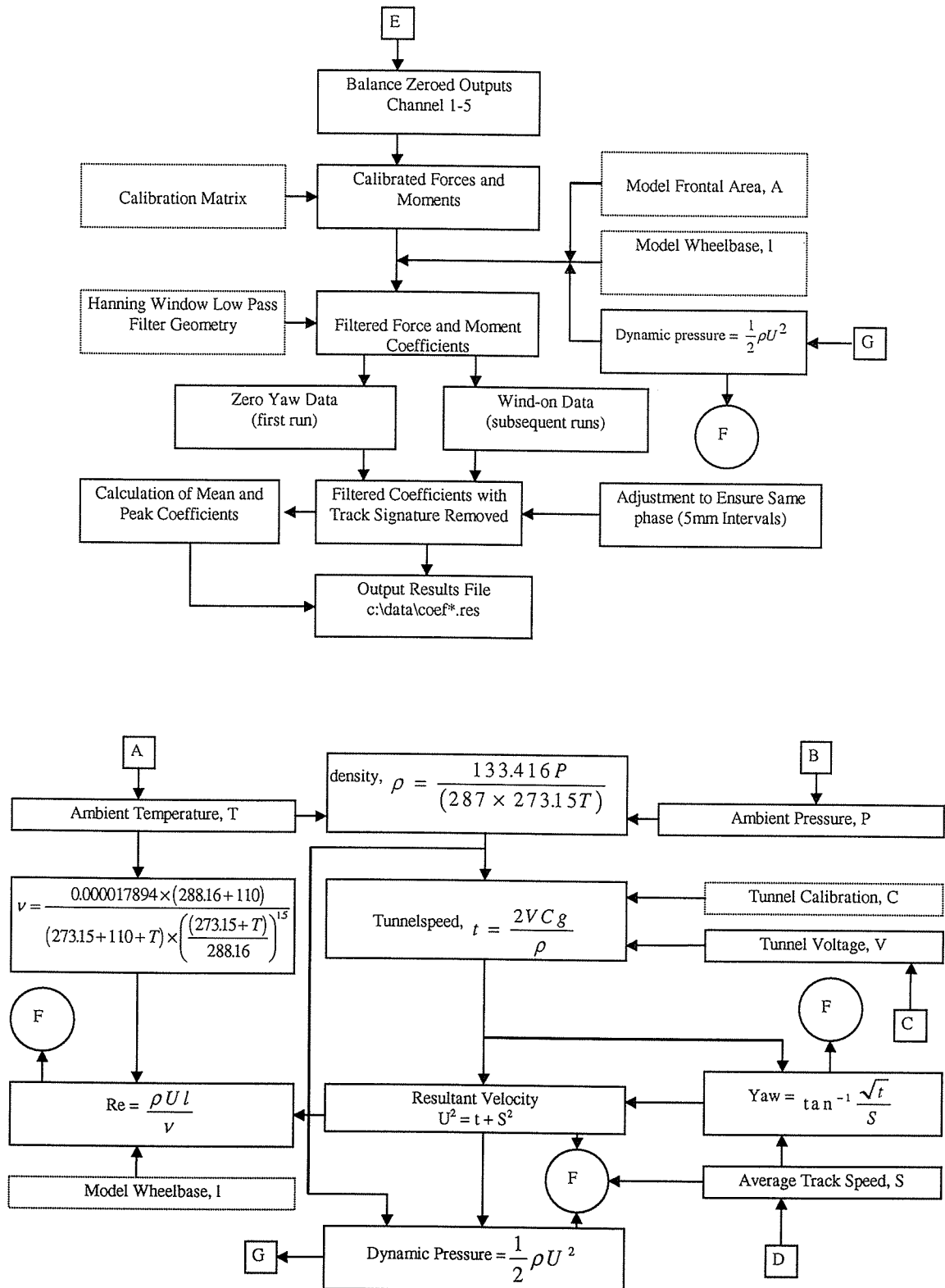


Figure B-2 Typical Sensor Technics SLP010DD4 Pressure Calibration

Appendix C: Program Listings

During the course of the research program, numerous computer programs were used for the reduction of data. The majority of programs are written in Matlab and listings for typical data reduction are included below. Also included is the Fortran program that converts data created by Matlab into a format suitable for Fieldview and generates the Fieldview grid. The general form of all force and pressure data reduction is illustrated in these flow charts:





Dynamic Pressure Data Reduction of Radiused 1-Box Model

% Matlab program for analysis of CROSS WIND TRACK pressure data written by ADChadwick November 1997

% Modified from matlab force reduction program by A R Macklin Summer 1996

pack

% Calibration matrix

```
calmax1=[ 17.22 0 0 0 0 0 %calibrated to pascals
          0 10.70 0 0 0
          0 0 31.75 0 0
          0 0 0 25.05 0
          0 0 0 0 38.23];
```

% Position of LED sensors at the side of the track

```
ledposn=[0 0.527 0.516 0.561 0.514 0.547 0.641 0.602 0.470];
```

% Ambient pressure and temperature for this test

```
press=1000;
```

```
temp=15;
```

% Counters

```
resfileheader=0;
```

```
filecoeffheader=0;
```

```
holdup=0;
```

```
currentdate=date;
```

```
average=1;
```

```
stopit=0;
```

% Text file which contains a list of the data files

% This is for leeward face, similar programs convert windward, top bottom, rear and front faces

```
filenames=c:\data\roundbox\rbbox20l.txt';
```

% Directory that the data files are kept in

```
directory=c:\data\roundbox\';
```

```
sdirectory=size(directory,2);
```

% Text file that contains dynamic pressure correction data

```
pccorrectfile=c:\data\plate\pccorrect.txt';
```

```
tunnelqdat=fopen(pccorrectfile,'rt');
```

```
tunnelqcor=fscanf(tunnelqdat,'%g',[5,226]);
```

```
fclose(tunnelqdat);
```

% Text file that contains static pressure correction data

```
spccorrectfile=c:\data\plate\spccorrect.txt';
```

```
tunnelpdata=fopen(spccorrectfile,'rt');
```

```
statpdata=fscanf(tunnelpdata,'%g %g %g %g %g',[5,226]);
```

```
fclose(tunnelpdata);
```

% Text file that contains tubing frequency response correction data

```
freqdat=c:\data\freqtube\boxfreq.txt';
```

```
freqdata=fopen(freqdat,'rt');
```

```
freqda=fscanf(freqdata,'%g %g',[2,1024]);
```

```
fclose(freqdata);
```

```
freqda=freqda;
```

```
atube(1:1024,1)=freqda(1:1024,1)+(freqda(1:1024,2)*i);
```

```
clear freqda;
```

% Results file for mean test data

```
resultsfile=c:\data\pressure\zeropres.res';
```

% Results file for mean pressure contour maps

```
filecoeff=c:\data\pressure\means.res';
```

% Results file for dynamic force integrated from pressure distribution

```
pfiler=c:\data\pressure\pforce';
```

% Results files for dynamic moments integrated from pressure distribution

```
pmfiler=c:\data\pressure\pmomentbx';
```

```
pmfiler=c:\data\pressure\pmomenty';
```

% Results file for calculated dynamic peak pressures

```
ppfiler=c:\data\pressure\ppeak';
```

% Reads the text file that contains the filenames

```
fnames=fopen(filenames,'r');
```

```
repeat=0;
```

```
n=1;
```

```
while n<=66 %determines number of runs processed
```

```
    filen(n,:)=fscanf(fnames,'%s',1);
```

```
    n=n+1;
```

```
end
```

```
[p,q]=size(filen);
```

```
nofiles=n-1;
```

```
fprintf('\n%g files will be processed \n',nofiles);
```

```
fclose(fnames);
```

```

% Start of processing of test data. 2 files per run; 1 run, 1 windoff
for pfileno=1:nfiles/2
    % Reading filename list
    fsourcefile=filen((2*pfileno-1),:);
    sfsourcefile=size(fsourcefile,2);
    for n=1:sdirectory
        sourcefile(1,n)=directory(1,n);
    end
    for n=sdirectory+1:sfsourcefile+sdirectory
        sourcefile(1,n)=fsourcefile(1,n-sdirectory);
    end
    fzero1file=filen((2*pfileno),:);
    sfzero1file=size(fzero1file,2);
    for n=1:sdirectory
        zero1file(1,n)=directory(1,n);
    end
    for n=sdirectory+1:sfzero1file+sdirectory
        zero1file(1,n)=fzero1file(1,n-sdirectory);
    end
    fprintf('the data file is %s\n',sourcefile)
    fprintf('the zero file is %s\n',zero1file)

    % Reading raw data
    sfile=fopen(sourcefile,'r');
    hdataset=fscanf(sfile,'%s',[1,2]);
    hvers=fscanf(sfile,'%s',[1,2]);
    hnumseries=fscanf(sfile,'%s',[1,2]);
    hstorage=fscanf(sfile,'%s',[1,2]);
    hsername=fscanf(sfile,'%s',[1,2]);
    hunits=fscanf(sfile,'%s',[1,2]);
    hinterval=fscanf(sfile,'%s',1);
    timeint=fscanf(sfile,'%g',1);
    hcomment=fscanf(sfile,'%s',1);
    mmwater=fscanf(sfile,'%g',1);
    % Tunnel dynamic pressure in mmwater
    comment=fscanf(sfile,'%s',1); % Test information eg leeward face
    boxtappings=fscanf(sfile,'%g',[1,5]); % Tapping numbers tested
    hdata=fscanf(sfile,'%s',1);
    fprintf('Header check... DATA = %s\n',hdata);
    rawdata=fscanf(sfile,'%g %g %g %g %g %g',[6 inf]);
    nosamp=size(rawdata,2);
    fclose(sfile);
    % Reading wind-off data
    fprintf('Averaging zeros....\n')
    z1file=fopen(zero1file,'r');
    z1hdata=fscanf(z1file,'%s',[1,4]);
    z1data=fscanf(z1file,'%g,%g,%g,%g,%g',[6 inf]);
    lenz1data=size(z1data,2);
    avz1data=mean(z1data);
    % Takes average of all wind-off data per channel
    stdevz1=std(z1data);
    clear z1hdata;
    clear z1data;
    clear lenz1data;
    fclose(z1file);
    avzdata=avz1data;
    avzdata=avzdata';
    avzdata(6,1)=0;
    % Subtracts wind-offs from rawdata
    for m=1:6
        for n=1:nosamp
            rawdata(m,n)=rawdata(m,n)-avzdata(m);
        end
    end
    clear avzdata;
    % Works out speed of model across track using LED positions and trigger channel 6
    fprintf('Working out speeds....\n')
    count=1;
    down=0;
    up=0;
    for n=10:nosamp-10;
        if rawdata(6,n)>25

```

```

    if rawdata(6,n+1)<25
        count=count+1;
        timeled(count)=(n+1)*timeint;
        down=down+1;
        dsample(down)=n;
    end
end
if rawdata(6,n)<25
    if rawdata(6,n+1)>25
        count=count+1;
        timeled(count)=(n+1)*timeint;
        up=up+1;
        usample(up)=n;
    end
end
end
ledno=count;
for led=2:ledno-1
    speed(led-1)=ledposn(led)/(timeled(led)-timeled(led-1));
end
for countspeed=1:7
    averagesp(countspeed)=speed(countspeed);
end
avgspeed=mean(averagesp);
% Printing model speeds to screen
for led=2:ledno-2
    fprintf('%6.2f\n',speed(led-1));
end
fprintf('average speed is %6.2f\n',avgspeed);
% Calculates distance between each sample
rawdata=rawdata';
rawdata(:,2:6)=rawdata(:,1:5);
for n=1:dsample(1)
    rawdata(n,1)=ledposn(2)*n/dsample(1);
end
for n=dsample(1):usample(1)
    rawdata(n,1)=rawdata(dsample(1),1)+ledposn(3)*(n-
        dsample(1))/(usample(1)-dsample(1));
end
for n=usample(1):dsample(2)
    rawdata(n,1)=rawdata(usample(1),1)+ledposn(4)*(n-
        usample(1))/(dsample(2)-usample(1));
end
for n=dsample(2):usample(2)
    rawdata(n,1)=rawdata(dsample(2),1)+ledposn(5)*(n-
        dsample(2))/(usample(2)-dsample(2));
end
for n=usample(2):dsample(3)
    rawdata(n,1)=rawdata(usample(2),1)+ledposn(6)*(n-
        usample(2))/(dsample(3)-usample(2));
end
for n=dsample(3):usample(3)
    rawdata(n,1)=rawdata(dsample(3),1)+ledposn(7)*(n-
        dsample(3))/(usample(3)-dsample(3));
end
for n=usample(3):dsample(4)
    rawdata(n,1)=rawdata(usample(3),1)+ledposn(8)*(n-
        usample(3))/(dsample(4)-usample(3));
end
for n=dsample(4):usample(4)
    rawdata(n,1)=rawdata(dsample(4),1)+ledposn(9)*(n-
        dsample(4))/(usample(4)-dsample(4));
end
for n=usample(4):dsample(5)
    rawdata(n,1)=rawdata(usample(4),1)+(n-
        usample(4))*timeint*speed(ledno-2);
end
% Defines lowpass Hamming window filter
pass=30;
trans=10;
a=0.232;
nptpass=round(pass*timeint*2048);
npttrans=round(trans*timeint*2048);

```



```

ham=zeros(1,2048);
for n=1:nptpass
    ham(n)=1;
end
for n=nptpass:nptpass+npttrans
    ham(n)=1+2*a*(cos(pi*(n-nptpass)/npttrans)-1);
end
for n=nptpass+npttrans:2048-(nptpass+npttrans)
    ham(n)=0;
end
for n=2048-(nptpass+npttrans):2048-nptpass
    ham(n)=1+2*a*(cos(pi+pi*(n-(2048-(nptpass+npttrans)))/npttrans)-1);
end
for n=2048-nptpass:2048
    ham(n)=1;
end
ham=ham';
% Filtering of rawdata
fprintf('Filtering...\n')
% Takes fast fourier transform of the data
ftdata=fft(rawdata(:,2:6),2048);
% Corrects frequency response of different tube lengths
    (atube=250mm - etube=450mm)
% For dynamic tests all tube lengths are 250mm
for x=1:5
    for a=1:1024
        ftdata(a,x)=ftdata(a,x)/atube(a,1);
    end
end
% Applies Hamming window to the data
realftdata=zeros(2048,5);
imagftdata=zeros(2048,5);
for m=1:5
    for n=1:2048
        realftdata(n,m)=real(ftdata(n,m))*ham(n);
        imagftdata(n,m)=imag(ftdata(n,m))*ham(n);
    end
end
clear ftdata;
%takes the inverse fft of the filtered data
frdata=realftdata+i*imagftdata;
condata(:,2:6)=ifft(frdata(:,1:5));
condata(1:1366,1)=rawdata(1:1366,1);
clear frdata;
clear realftdata;
clear imagftdata;
% Interpolating each run to the same positional characteristics
datapping(1,2:6)=condata(1,2:6);
inter=0.02; %sets interpolation interval (20mm)
x=inter;
y=1;
z=2;
stop=0;
continue=0;
while continue==0
    if condata(z,1)<x
        z=z+1;
    else
        y=y+1;
        datapping(y,2:6)=condata(z-1,2:6)+((condata(z,2:6)- condata(z-1,2:6))*
            (x-condata(z-1,1))/(condata(z,1)-condata(z-1,1)));
        datapping(y,1)=x;
        x=x+inter;
        if x>4.51
            continue=1;
        end
    end
end
clear condata;
% Averaging 3 runs
if average==1
    datapping1=datapping;
    clear datapping;

```



```

average=2;
elseif average==2
    datapping2=datapping;
    clear datapping;
    average=3;
elseif average==3
    datapping3=datapping;
    datav(:,1)=datapping1(:,1);
    datav(:,2:6)=(datapping1(:,2:6)+datapping2(:,2:6)+datapping3(:,2:6))/3;
    clear datapping1;
    clear datapping2;
    clear datapping3;
    clear datapping;
    average=1;
% Test data results file header information
resfile=fopen(resultsfile,'a');
while resfileheader==0
    fprintf(resfile,'Dataset %s processed on %s \n',filenames,currentdate);
    fprintf(resfile,'sourcefile,header,zerofile, ch1zero,ch2zero,ch3zero,ch4zero,ch5zero,ch6zero,');
    fprintf(resfile,'ch1d1,ch2d1,ch3d1,ch4d1,ch5d1,ch6d1,');
    fprintf(resfile,'sp1-2,sp2-3,sp3-4,sp4-5,sp5-6,sp6-7,sp7-8,sp8-9,');
    fprintf(resfile,'AvgTrackspeed(m/s),Tunnelspeed(m/s),Resultant Speed(m/s),
        Tunnel q(Pa),Track q(Pa),Resultant q(Pa),Yaw(deg),Re,');
    fprintf(resfile,'Cp1,Cp2,Cp3,Cp4,Cp5,Node1,Node2,Node3,Node4,Node5\n');
    resfileheader=1;
end
% Saving average wind-off data to the test data results file
fprintf(resfile,'%s,%s',fsourcefile,comment);
fprintf(resfile,'%s',fzero1file);
fprintf(resfile,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f',avz1data);
fprintf(resfile,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f',stdevz1);
clear avz1data;
clear stdevz1;
% Saving speeds to test data results file
for led=2:ledno-1
    fprintf(resfile,'%6.2f',speed(led-1));
end
fprintf(resfile,'%6.2f',avgspeed);
% Test data
density=1.225*press*288/(1000*(273+temp));
% Pressure in mbar, temp in degC
for x=1:226
    tunnelq(x)=9.80665*mmwater*tunnelqcor(x);
    %Dynamic pressure corrected for variation across gust
end
tunnelspeed=(2*tunnelq(113)/density)^0.5;
% Tunnel speed in m/s
yaw=180*atan(tunnelspeed/avgspeed)/pi;
% Resultant Yaw angle in degrees
resultantspeed=(tunnelspeed^2+avgspeed^2)^0.5;
% Resultant speed in m/s
trackq=0.5*density*avgspeed^2;
% Dynamic pressure based on speed of model in Pascals
for x=1:226
    resultantq(x)=tunnelq(x)+trackq; % Resultant dynamic pressure in Pascals
end
viscosity=0.00017894*(288.16+110)/(273.15+temp+110)*((273.15+temp)/288.16)^1.5;
Re=density*resultantspeed*0.4/viscosity;% Based on square root of frontal area
% Saving results to the test data results file
fprintf(resfile,'%6.2f,%6.2f,%6.2f,%6.2f,%6.2f,%6.2f,%6.4f',
    tunnelspeed,resultantspeed,tunnelq(113),trackq,resultantq(113),yaw,Re);
fclose(resfile);
datav=datav';
% Works out position of pressure tapping for static and dynamic pressure corrections
boxtappingsa(:,:)=boxtappings(:,:);
for x=1:5
    goon=0;
    while goon==0
        if boxtappingsa(1,x)>5
            boxtappingsa(1,x)=boxtappingsa(1,x)-5;
        elseif boxtappingsa(1,x)<=5
            goon=1;
        end
    end
end

```

```

    end
end

% Calibrates the transducer output voltage to Pascals
for x=1:226
    datav(2:6,x)=calmax1*datav(2:6,x);
% Non dimensionalise pressures to Cp's and accounts for static pressure variation
    for y=1:5
        if boxtappingsa(y)==1
            datav(y+1,x)=(datav(y+1,x)-(statpdat(1,x)*tunnelq(x))-(0.08*tunnelq(x)))/resultantq(x);
        elseif boxtappingsa(y)==2
            datav(y+1,x)=(datav(y+1,x)-(statpdat(2,x)*tunnelq(x))-(0.08*tunnelq(x)))/resultantq(x);
        elseif boxtappingsa(y)==3
            datav(y+1,x)=(datav(y+1,x)-(statpdat(3,x)*tunnelq(x))-(0.08*tunnelq(x)))/resultantq(x);
        elseif boxtappingsa(y)==4
            datav(y+1,x)=(datav(y+1,x)-(statpdat(4,x)*tunnelq(x))-(0.08*tunnelq(x)))/resultantq(x);
        elseif boxtappingsa(y)==5
            datav(y+1,x)=(datav(y+1,x)-(statpdat(5,x)*tunnelq(x))-(0.08*tunnelq(x)))/resultantq(x);
        end
    end
end
datav=datav';
% Calculating mean pressure coefficients between 1m and 2m into the gust
for coefficient=1:5
    meancoeff(1,coefficient)=mean(real(datav(100:150,(coefficient+1)))));
end
% Saving mean pressure results to the test data results file
resfile=fopen(resultsfile,'a');
fprintf(resfile,'%6.2f,%6.2f,%6.2f,%6.2f,%6.2f',meancoeff(:,:));
fprintf(resfile,'%6.0f,%6.0f,%6.0f,%6.0f,%6.0f\n',boxtappings(:,:));
fclose(resfile);
% Collate meanmap and transient data ready for fieldview plotting
if stopit==0
    fvdat=zeros(55,226);
    meanmap=zeros(55,1);
    stopit=1;
end
[fat tubby]=size(fvdat);
for coefficient=1:5
    meanmap(boxtappings(1,(coefficient)),1)=meancoeff(1,coefficient);
end
datav=datav';
for coefficient=1:5
    fvdat(boxtappings(1,coefficient),:)=real(datav((coefficient+1),:));
end
clear datav;
end
end
% For the rounded box case the edge tappings are at the apex of the radius and data needs saving for top and bottom
faces
fvdatb(1:5:51,:)=fvdat(5:5:55,:);
fvdatb(5:5:55,:)=fvdat(1:5:51,:);
meanmapb(1:5:51,:)=meanmap(5:5:55,:);
meanmapb(5:5:55,:)=meanmap(1:5:51,:);
% Converts data from column to xy format
for x=1:11
    for y=1:5
        meanp(x,y)=meanmap((5*(x-1)+y),1);
    end
end
meanp=meanp';
% Interpolation parameters
x=[-0.237 -0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2 0.237];
y=[-0.097 -0.05 0 0.05 0.097];
xi=-0.237:0.00948:0.237;
yi=-0.097:0.0097:0.097;
yi=yi';
% Interpolation to 10mm spacings
meanmap=interp2(x,y,meanp,xi,yi,'cubic');
clear meanp;
% Calculation of force acting on plate by summation of pressures
forcemap=meanmap/446.25; % 446.25 is derived from pressure area of each element
coforcex=sum(forcemap);

```

```

forcemap=forcemap';
coforcey=sum(forcemap);
force=sum(coforcex);
% Centroids of pressure
for a=1:51
    cx(a)=coforcex(a)*xi(a);
end
for a=1:21
    cy(a)=coforcey(a)*yi(a);
end
sumcx=sum(cx)/force;
sumcy=sum(cy)/force;
% Calculation of moments in x and y
momentcoeffx=sumcx*force;
momentcoeffy=sumcy*force;
% Saving the mean pressuee map
fprintf('Saving mean data....\n');
fileco=fopen(filecoeff,'a');
while filecoeffheader==0;
    fprintf(fileco,'Dataset %s processed on %s \n',filenames,
        currentdate);
    filecoeffheader=1;
end
meanmap=meanmap';
fprintf(fileco,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,\n',meanmap(:,:));
clear meanmap;
fclose(fileco);
% Converts fieldview data from column to xy format
for n=1:(tubby-1)
    for x=1:11
        for y=1:5
            fvddata(x,y)=fvdat((5*(x-1)+y),n);
        end
    end
    % Interpolation parameters
    y=[-0.237 -0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2 0.237];
    x=[-0.097 -0.05 0 0.05 0.097];
    yi=-0.237:0.00948:0.237;
    xi=-0.097:0.0097:0.097;
    yi=yi';
    % Interpolating to 10mm spacing
    transmap=interp2(x,y,fvddata,xi,yi,'cubic');
    % Calculates peak pressure and distance to peak
    [x,y]=max(transmap);
    [a,b]=max(x);
    maxpeakcp=a;
    distmaxpeakcp=x-y(b)*0.00948;
    transmap=transmap';
    [x,y]=max(transmap);
    [a,b]=max(x);
    distmaxpeakcpy=y(b)*0.0097;
    transmap=transmap';
    [x,y]=min(transmap);
    [a,b]=min(x);
    minpeakcp=a;
    distminpeakcp=x-y(b)*0.00948;
    transmap=transmap';
    [x,y]=min(transmap);
    [a,b]=min(x);
    distminpeakcpy=y(b)*0.0097;
    transmap=transmap';
    % Calculates transient forces and moments
    forcemap=transmap/446.25; % 446.25 derived from area of pressure element
    coforcex=sum(forcemap);
    forcemap=forcemap';
    coforcey=sum(forcemap);
    force=sum(coforcex);
    % Calculation of centroids of pressure
    for a=1:51
        cx(a)=coforcey(a)*yi(a);

```



```

end
for a=1:21
    cy(a)=coforcecx(a)*xi(a);
end
sumcx=sum(cx)/force;
sumcy=sum(cy)/force;
% Calculation of Moments
momentcoeffx=sumcx*force;
momentcoeffy=sumcy*force;
% Saving pressure force data
presforc=fopen(pffile,'a');
while holdup==0;
    fprintf(presforc,'Dataset %s processed on %s \n',filenames,currentdate);
    fprintf(presforc,'%s,%6.1f,',comment,yaw);
    holdup=1;
end
fprintf(presforc,'%6.3f, ',force(:,,:));
fclose(presforc);
% Saving moment data
presmomentx=fopen(pmfile,'a');
while holdup==1
    fprintf(presmomentx,'Dataset %s processed on %s \n',filenames,currentdate);
    fprintf(presmomentx,'%s,%6.1f,',comment,yaw);
    holdup=2;
end
fprintf(presmomentx,'%6.4f, ',momentcoeffx(:,,:));
fclose(presmomentx);
presmomenty=fopen(pmfile,'a');
while holdup==2
    fprintf(presmomenty,'Dataset %s processed on %s \n',filenames,currentdate);
    fprintf(presmomenty,'%s,%6.1f,',comment,yaw);
    holdup=3;
end
fprintf(presmomenty,'%6.4f, ',momentcoeffy(:,,:));
fclose(presmomenty);
% Saving pressure peak data
prespeak=fopen(ppfile,'a');
while holdup==3;
    fprintf(prespeak,'Dataset %s processed on %s \n',filenames,currentdate);
    fprintf(prespeak,'Dist(m),maxpeakcp,distmaxpeakcp(m), distmaxpeakcpy(m),');
    fprintf(prespeak,'minpeakcp,distminpeakcp(m), distminpeakcpy(m)\n');
    holdup=4;
end
fprintf(prespeak,'%6.2f,%6.2f,%6.2f,%6.2f,',(n*0.02),maxpeakcp, distmaxpeakcp,distmaxpeakcpy);
fprintf(prespeak,'%6.2f,%6.2f,%6.2f,%6.2f \n',minpeakcp,distminpeakcp, distminpeakcpy);
fclose(prespeak);
clear presforce;
% Corrects geometry of interpolation of leeward face for fieldview
plotting (also used for bottom face)
for y=1:21
    transmapa(:,y)=transmap(:,abs(22-y));
end
clear transmap;
% Saves fieldview data
fv=fopen(fvfile,'a');
fprintf(fv,'%6.2f\n',transmapa(:,,:));
fclose(fv);
clear transmapa;
end
% Adds carriage return to results files
presforc=fopen(pffile,'a');
fprintf(presforc,'\n');
fclose(presforc);
presmomentx=fopen(pmfile,'a');
fprintf(presmomentx,'\n');
fclose(presmomentx);
presmomenty=fopen(pmfile,'a');
fprintf(presmomenty,'\n');
fclose(presmomenty);

```

Steady State Pressure Reduction of Radiused 1-Box Model

% Matlab program for analysis of steady state CROSS WIND TRACK pressure data written by ADChadwick November 1997

% Modified from matlab force reduction program by A R Macklin Summer 1996

```
clear all
pack
% calibration matrix
calmax1=[25.05 0 0 %calibrated to pascals
        0 31.75 0
        0 0 10.7];
% Counters
resfileheader=0;
filecoeffheader=0;
stdevheader=0;
stopit=0;
currentdate=date;
scani=1;
% Text file which contains the data
sourcefile='c:\data\roundbox\0roundcheck.txt';
% Directory that the data files are kept in
dir='c:\data\roundbox\';
sdir=size(dir,2);
% File to put mean pressure contour maps in
resultsfile='c:\data\pressure\static\more.res';
filecoeff='c:\data\pressure\static\means.res';
xtra='c:\data\pressure\static\extra.res';
% Text file that contains pressure tapping identification matrix
tappingsfile='c:\data\roundbox\rboxtapping.txt';
tappingsdata=fopen(tappingsfile,'rt');
boxtappings=fscanf(tappingsdata,'%g %g %g %g %g %g',[6,96]);
fclose(tappingsdata);
% Ambient temp and pressure
press=1009;
temp=11;
% Reads the rawdata
sfile=fopen(sourcefile,'r');
rawdata=fscanf(sfile,'%g %g %g %g',[4 96]);
fclose(sfile);
% Calibrates the data
fprintf('Calibrating...\n')
rawdat(1:3,:)=100*rawdata(1:3,:);
mmwater=100*rawdata(4,:);
clear rawdata;
convdata=calmax1*rawdat;
clear rawdat;
% Test Data
density=1.225*press*288/(1000*(273+temp));
% Pressure in mbar, temp in degC
viscosity=0.000017894*(288.16+110)/(273.15+temp+110)*((273.15+temp)/288.16)^1.5;
for x=1:96
    tunnelq(x)=9.80665*mmwater(x)*0.9834;
    %0.9834 accounts for difference in q from measuring point to track
    convdata(1:3,x)=(convdata(1:3,x)/tunnelq(x))-0.08; %0.08 accounts
    % for diff in static pressure from pitot to plane of track
    tunnelspeeds(x)=(2*tunnelq(x)/density)^0.5;
    Res=density*tunnelspeeds*0.4/viscosity;
end
tunnelspeed=mean(tunnelspeeds);
Re=mean(Res);
% Saving results to the test data results file
fprintf('Saving results...\n')
resfile=fopen(resultsfile,'a');
while resfileheader==0;
    fprintf(resfile,'Dataset %s processed on %s\n',sourcefile,currentdate);
    fprintf(resfile,'Tunnelspeed(m/s), Tunnelq(Pa), Density(kg/m3), Re\n');
    fprintf(resfile,'%6.2f,%6.2f,%6.2f,%6.4f\n',tunnelspeed,tunnelq(1),density,Re);
    fprintf(resfile,'mean1,mean2,mean3\n');
    resfileheader=1;
end
```

```

fprintf(resfile,'%6.3f,%6.3f,%6.3f\n',convdata(:,:));
fprintf(resfile,'\n');
fclose(resfile);
% Generates pressure map matrices for each face
if stopit==0
    meanmapw=zeros(55,1);
    meanmapl=zeros(55,1);
    meanmapt=zeros(55,1);
    meanmapb=zeros(55,1);
    meanmapf=zeros(25,1);
    meanmapr=zeros(25,1);
    stopit=1;
end
% Identifies pressure tappings
for coefficient=1:3
    for scani=1:96
        if boxtappings(coefficient,scani)==3
            meanmapw(boxtappings((coefficient+3),scani),1)=convdata(coefficient,scani);
        elseif boxtappings(coefficient,scani)==2
            meanmapl(boxtappings((3+coefficient),scani),1)=convdata(coefficient,scani);
        elseif boxtappings(coefficient,scani)==4
            meanmapt(boxtappings((3+coefficient),scani),1)=convdata(coefficient,scani);
        elseif boxtappings(coefficient,scani)==1
            meanmapb(boxtappings((3+coefficient),scani),1)=convdata(coefficient,scani);
        elseif boxtappings(coefficient,scani)==5
            meanmapf(boxtappings((3+coefficient),scani),1)=convdata(coefficient,scani);
        elseif boxtappings(coefficient,scani)==6
            meanmapr(boxtappings((3+coefficient),scani),1)=convdata(coefficient,scani);
        end
    end
end
%For radiused model, tappings are at apex of radius and need duplicating from lee and windward to top and bottom
for x=1:5
    meanmapw((50+x),1)=meanmapf(x,1);
    meanmapw(x,1)=meanmapr((20+x),1);
    meanmapl((50+x),1)=meanmapf((26-x),1);
    meanmapl(x,1)=meanmapr((6-x),1);
    meanmapt(x,1)=meanmapr((6-x)*5,1);
    meanmapt((50+x),1)=meanmapf(x*5,1);
    meanmapb(x,1)=meanmapr((1+((x-1)*5),1);
    meanmapb(50+x,1)=meanmapf((1+((5-x)*5),1);
    meanmapb((1+((x-1)*5),1)=meanmapl(((x+1)*5),1);
    meanmapb((5*(x+5)+1),1)=meanmapl(((5*(x+5)+5),1);
    meanmapt((1+((x-1)*5),1)=meanmapw(((x*5)+5),1);
    meanmapt(((x*5)+5),1)=meanmapl((1+((x-1)*5),1);
    meanmapb(((x*5)+5),1)=meanmapw((1+((x-1)*5),1);
end
% Converts data from column to xy format
for x=1:11
    for y=1:5
        meanpl(x,y)=meanmapl((5*(x-1)+y),1);
        meanpb(x,y)=meanmapb((5*(x-1)+y),1);
        meanpt(x,y)=meanmapt((5*(x-1)+y),1);
        meanpw(x,y)=meanmapw((5*(x-1)+y),1);
    end
end
for x=1:5
    for y=1:5
        meanpr(x,y)=meanmapr((5*(x-1)+y),1);
        meanpf(x,y)=meanmapf((5*(x-1)+y),1);
    end
end
meanpl=meanpl';
meanpb=meanpb';
meanpt=meanpt';
meanpw=meanpw';
meanpf=meanpf';
meanpr=meanpr';
% Interpolation parameters
x=[-0.237 -0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2 0.237];
y=[-0.097 -0.05 0 0.05 0.097];
z=[-0.097 -0.05 0 0.05 0.097];
xi=-0.237:0.00948:0.237;

```

```

yi=-0.097:0.0097:0.097;
zi=-0.097:0.0097:0.097;
yi=yi';
% Interpolation to 10mm spacings
meanmapl=interp2(x,y,meanpl,xi,yi,'cubic');
meanmapb=interp2(x,y,meanpb,xi,yi,'cubic');
meanmapt=interp2(x,y,meanpt,xi,yi,'cubic');
meanmapw=interp2(x,y,meanpw,xi,yi,'cubic');
meanmapr=interp2(z,y,meanpr,zi,yi,'cubic');
meanmapf=interp2(z,y,meanpf,zi,yi,'cubic');
% Calculation of force acting on each face by summation of pressures
forcemapl=meanmapl/446.25;
coforcex=sum(forcemapl);
forcemapl=forcemapl';
coforcey=sum(forcemapl);
forcef=sum(coforcex);
forcemapb=meanmapb/446.25;
coforcebx=sum(forcemapb);
forcemapb=forcemapb';
coforceby=sum(forcemapb);
forceb=sum(coforcebx);
forcemapt=meanmapt/446.25;
coforcetx=sum(forcemapt);
forcemapt=forcemapt';
coforcety=sum(forcemapt);
forcetf=sum(coforcetx);
forcemapw=meanmapw/446.25;
coforcewx=sum(forcemapw);
forcemapw=forcemapw';
coforcewy=sum(forcemapw);
forcew=sum(coforcewx);
forcemapf=meanmapf/441;
coforcefx=sum(forcemapf);
forcemapf=forcemapf';
coforcefy=sum(forcemapf);
forcef=sum(coforcefx);
forcemapr=meanmapr/441;
coforcerox=sum(forcemapr);
forcemapr=forcemapr';
coforcery=sum(forcemapr);
forcerf=sum(coforcerox);
% Calculations of centroids and moments for each face about central axes of model
for a=1:51
    clx(a)=coforcex(a)*xi(a);
    cbx(a)=coforcebx(a)*xi(a);
    ctx(a)=coforcetx(a)*xi(a);
    cwx(a)=coforcewx(a)*xi(a);
end
for a=1:21
    crx(a)=coforcerox(a)*zi(a);
    cfx(a)=coforcefx(a)*zi(a);
end
for a=1:21
    cly(a)=coforcey(a)*yi(a);
    cby(a)=coforceby(a)*yi(a);
    cty(a)=coforcety(a)*yi(a);
    cwy(a)=coforcewy(a)*yi(a);
    cry(a)=coforcery(a)*yi(a);
    cfy(a)=coforcefy(a)*yi(a);
end
cenlx=sum(clx)/forcef;
cenly=sum(cly)/forcef;
cenwx=sum(cwx)/forcew;
cenwy=sum(cwy)/forcew;
cenrx=sum(crx)/forcerf;
cenry=sum(cry)/forcerf;
centx=sum(ctx)/forcetf;
centy=sum(cty)/forcetf;
cenbx=sum(cbx)/forceb;
cenby=sum(cby)/forceb;
cenfx=sum(cfx)/forcef;
cenfy=sum(cfy)/forcef;
% Calculation of moments in x and y

```


[illegible]

Dynamic Force Data Reduction of Radiused 1-Box Model

% Matlab program for analysis of CROSS WIND TRACK dynamic force data written by ADChadwick November 1998
Modified from matlab force reduction program by A R Macklin

```
clear all
% Calibration matrix
dat=[ 0.503 -3.7258 0 0 0 0 %calibrated to N & Nm
      0.464 3.6965 0 0 0 0
      0 0 -0.4594 3.2958 0 0
      0 0 -0.4966 -3.4359 0 0
      0 0 0 0 -9.327 0
      0 0 0 0 0 1];

calmax1=inv(dat);
% Position of LED sensors at the side of the track
ledposn=[0 0.527 0.516 0.561 0.514 0.547 0.641 0.602 0.470];
% Counters
resfileheader=0;
filecoeffheader=0;
hay=1;
fat=1;
average=1;
currentdate=date;
% Text file which contains a list of the data files
filenames='z:\data\roundbox\force\dynrbf.txt';
% Directory that the data files are kept in
directory='z:\data\roundbox\force\';
sdirectory=size(directory,2);
% Results file for mean test data
resultsfile='z:\data\force\dynforce.res';
% Results files for dynamic test data
liftcoeff='z:\data\force\lift.res';
pitchcoeff='z:\data\force\pitch.res';
sidecoeff='z:\data\force\side.res';
yawcoeff='z:\data\force\yaw.res';
rollcoeff='z:\data\force\roll.res';
fnames=fopen(filenames,'r'); % Reads the text file that contains the filenames
repeat=0;
n=1;
while n<=36 %determines number of runs processed
    filen(n,:)=fscanf(fnames,'%s',1);
    n=n+1;
end
[p,q]=size(filen);
nofiles=n-1;
fprintf('\n%g files will be processed \n',nofiles);
fclose(fnames);
press=1009; temp=16; % Ambient pressure and temperature
% Start of processing of test data. 2 files per run; 1 run, 1 windoff
for pfileno=1:nofiles/2
    % Reading filename list
    fsourcefile=filen((2*pfileno-1),:);
    sfsourcefile=size(fsourcefile,2);
    for n=1:sdirectory
        sourcefile(1,n)=directory(1,n);
    end
    for n=sdirectory+1:sfsourcefile+sdirectory
        sourcefile(1,n)=fsourcefile(1,n-sdirectory);
    end
    fzero1file=filen((2*pfileno),:);
    sfzero1file=size(fzero1file,2);
    for n=1:sdirectory
        zero1file(1,n)=directory(1,n);
    end
    for n=sdirectory+1:sfzero1file+sdirectory
        zero1file(1,n)=fzero1file(1,n-sdirectory);
    end
    fprintf('the data file is %s\n',sourcefile)
    fprintf('the zero file is %s\n',zero1file)
    sfile=fopen(sourcefile,'r'); % Reading raw data
    hdataset=fscanf(sfile,'%s',[1,2]);
```

```

hvers=fscanf(sfile,'%s',[1,2]);
hnumseries=fscanf(sfile,'%s',[1,2]);
hstorage=fscanf(sfile,'%s',[1,2]);
hsername=fscanf(sfile,'%s',[1,2]);
hunits=fscanf(sfile,'%s',[1,2]);
hinterval=fscanf(sfile,'%s',1);
timeint=fscanf(sfile,'%g',1);
hcomment=fscanf(sfile,'%s',1); % Test information
mmwater=fscanf(sfile,'%g',1); % Tunnel dynamic pressure in mmwater
hdata=fscanf(sfile,'%s',1);
fprintf('Header check... DATA = %s\n',hdata);
rawdata=fscanf(sfile,'%g %g %g %g %g %g',[6 inf]);
nosamp=size(rawdata,2);
fclose(sfile);
fprintf('Averaging zeros...\n') % Reading wind-off data
z1file=fopen(zero1file,'r');
z1hdata=fscanf(z1file,'%s',[1,4]);
z1data=fscanf(z1file,'%g %g %g %g %g %g',[6 inf]);
lenz1data=size(z1data,2);
avz1data=mean(z1data); % Takes average of all wind-off data per channel
stdevz1=std(z1data);
clear z1hdata;
clear z1data;
clear lenz1data;
fclose(z1file);
avzdata=avz1data;
avzdata=avzdata;
avzdata(6,1)=0;
for m=1:6
    for n=1:nosamp
        rawdata(m,n)=rawdata(m,n)-avzdata(m); % Subtracts wind-offs from rawdata
    end
end
clear avzdata;
% Works out speed of model across track using LED positions and trigger channel 6
fprintf('Working out speeds...\n')
count=1;
down=0;
up=0;
for n=10:nosamp-10;
    if rawdata(6,n)>25
        if rawdata(6,n+1)<25
            count=count+1;
            timeled(count)=(n+1)*timeint;
            down=down+1;
            dsample(down)=n;
        end
    end
    if rawdata(6,n)<25
        if rawdata(6,n+1)>25
            count=count+1;
            timeled(count)=(n+1)*timeint;
            up=up+1;
            usample(up)=n;
        end
    end
end
ledno=count;
for led=2:ledno-1
    speed(led-1)=ledposn(led)/(timeled(led)-timeled(led-1));
end
for countspeed=1:7
    averagesp(countspeed)=speed(countspeed);
end
avgspeed=mean(averagesp);

for led=2:ledno-2
    fprintf('%6.2f\n',speed(led-1)); % Printing model speeds to screen
end
fprintf('average speed is %6.2f\n',avgspeed);
% Test data
density=1.225*press*288/(1000*(273+temp)); % Pressure in mbar, temp in degC
tunnelq=9.80665*mmwater*0.9834; %0.9834 accounts for difference in q

```



```

tunnelspeed=(2*tunnelq/density)^0.5;
yaw=180*atan(tunnelspeed/avgspeed)/pi;
resultantspeed=(tunnelspeed^2+avgspeed^2)^0.5;
trackq=0.5*density*avgspeed^2;
resultantq=(0.5*density*resultantspeed^2);
viscosity=0.000017894*(288.16+110)/(273.15+temp+110)*((273.15+temp)/288.16)^1.5;
Re=density*resultantspeed*0.2/viscosity;
% calibrating the output voltage to forces and moments
rawdata(1:6,1:nosamp)=calmax1*rawdata(1:6,1:nosamp);
% Non dimensionalising
rawdata(1:5,1:nosamp)=rawdata(1:5,1:nosamp)/(resultantq*0.04);
rawdata(2,1:nosamp)=rawdata(2,1:nosamp)/0.48;
rawdata(4,1:nosamp)=rawdata(4,1:nosamp)/0.48;
rawdata(5,1:nosamp)=rawdata(5,1:nosamp)/0.2;
% Translating roll from body axes to groundplane
rawdata(5,:)=rawdata(5,:)+(rawdata(3,:)*0.13/0.2);
% Calculating average peaks and means
for coefficient=1:5
    meancoeff(coefficient)=mean(rawdata(coefficient,420:630));
end
resfile=fopen(resultsfile,'a'); % Saving results
while resfileheader==0
    fprintf(resfile,'Dataset %s processed on %s \n',filenames,currentdate);
    fprintf(resfile,'sourcefile,zero1file,ch1zero,ch2zero
        ,ch3zero,ch4zero,ch5zero,ch6zero,');
    fprintf(resfile,'ch1d1,ch2d1,ch3d1,ch4d1,ch5d1,ch6d1,');
    fprintf(resfile,'sp1-2,sp2-3,sp3-4,sp4-5,sp5-6,sp6-7,sp7-8,sp8-9,');
    fprintf(resfile,'Avg Trackspeed(m/s),Tunnelspeed(m/s),Resultant Speed(m/s),
        Tunnel q(Pa),Track q(Pa),Resultantq(Pa),Yaw(deg),Re,');
    fprintf(resfile,'Lift,Pitch,Side,Yaw,Roll\n');
    resfileheader=1;
end
fprintf(resfile,'%s,',sourcefile);
fprintf(resfile,'%s,',fzero1file);
fprintf(resfile,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f',avz1data);
fprintf(resfile,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f',stdevz1);
clear avz1data;
clear stdevz1;
for led=2:ledno-1
    fprintf(resfile,'%6.2f',speed(led-1));
end
fprintf(resfile,'%6.2f',avgspeed);
fprintf(resfile,'%6.2f,%6.2f,%6.2f,%6.2f,%6.2f,%6.4f',
    tunnelspeed,resultantspeed,tunnelq,trackq,resultantq,yaw,Re);
for coefficient=1:5
    fprintf(resfile,'%6.3f',meancoeff(coefficient));
end
fprintf(resfile,'\n');
fclose(resfile);
% Defines lowpass Hamming window filter
pass=20;
trans=10;
a=0.232;
nptpass=round(pass*timeint*2048);
nptrans=round(trans*timeint*2048);
ham=zeros(1,2048);
for n=1:nptpass
    ham(n)=1;
end
for n=nptpass+npttrans
    ham(n)=1+2*a*(cos(pi*(n-nptpass)/npttrans)-1);
end
for n=nptpass+npttrans:2048-(nptpass+npttrans)
    ham(n)=0;
end
for n=2048-(nptpass+npttrans):2048-nptpass
    ham(n)=1+2*a*(cos(pi+pi*(n-(2048-(nptpass+npttrans)))/npttrans)-1);
end
for n=2048-nptpass:2048
    ham(n)=1;
end
ham=ham';
% Filtering of rawdata

```

```

fprintf('Filtering...\n')
rawdata=rawdata';
ftdata=fft(rawdata(:,1:5),2048);
% multiplies the fft of the data with the filter
realftdata=zeros(2048,5);
imagftdata=zeros(2048,5);
for m=1:5
    for n=1:2048
        realftdata(n,m)=real(ftdata(n,m))*ham(n);
        imagftdata(n,m)=imag(ftdata(n,m))*ham(n);
    end
end
ftdata=realftdata+i*imagftdata;
clear realftdata;
clear imagftdata;
% Average of 3 runs and subtraction of zero yaw track signature
if fat==1;
    ftdata1=ftdata;
    fat=2;
elseif fat==2;
    ftdata2=ftdata;
    fat=3;
elseif fat==3;
    ftdata3=ftdata;
    ftdata0(:,:)=(ftdata1(:,:)+ftdata2(:,:)+ftdata3(:,:))/3;
    clear ftdata1;
    clear ftdata2;
    clear ftdata3;
    fat=4;
elseif fat==4
    ftdata1=ftdata;
    fat=5;
elseif fat==5
    ftdata2=ftdata;
    fat=6;
elseif fat==6
    fat=4;
    ftdata3=ftdata;
    ftdata(:,:)=(ftdata1(:,:)+ftdata2(:,:)+ftdata3(:,:))/3;
    clear ftdata1;
    clear ftdata2;
    clear ftdata3;
    ftdata(:,:)=ftdata(:,:)-ftdata0(:,:);
    condata=ifft(ftdata);
    clear ftdata;
% Calculates distance between each sample and transfers data to position domain
rawdata(:,2:6)=rawdata(:,1:5);
for n=1:dsample(1)
    rawdata(n,1)=ledposn(2)*n/dsample(1);
end
for n=dsample(1):usample(1)
    rawdata(n,1)=rawdata(dsample(1),1)+ledposn(3)*(n-dsample(1))/(usample(1)-dsample(1));
end
for n=usample(1):dsample(2)
    rawdata(n,1)=rawdata(usample(1),1)+ledposn(4)*(n-usample(1))/(dsample(2)-usample(1));
end
for n=dsample(2):usample(2)
    rawdata(n,1)=rawdata(dsample(2),1)+ledposn(5)*(n-dsample(2))/(usample(2)-dsample(2));
end
for n=usample(2):dsample(3)
    rawdata(n,1)=rawdata(usample(2),1)+ledposn(6)*(n-usample(2))/(dsample(3)-usample(2));
end
for n=dsample(3):usample(3)
    rawdata(n,1)=rawdata(dsample(3),1)+ledposn(7)*(n-dsample(3))/(usample(3)-dsample(3));
end
for n=usample(3):dsample(4)
    rawdata(n,1)=rawdata(usample(3),1)+ledposn(8)*(n-usample(3))/(dsample(4)-usample(3));
end
for n=dsample(4):usample(4)
    rawdata(n,1)=rawdata(dsample(4),1)+ledposn(9)*(n-dsample(4))/(usample(4)-dsample(4));
end
for n=usample(4):dsample(5)
    rawdata(n,1)=rawdata(usample(4),1)+(n-usample(4))*timeint*speed(ledno-2);

```

```

end
condata(:,2:6)=condata(:,1:5);
condata(1:1366,1)=rawdata(:,1);
clear rawdata;
% Interpolating values to the same positions (default = 20mm space)
datapping(1,2:6)=condata(1,1:5);
inter=0.02; %sets interpolation interval
x=inter; y=1; z=2; continue=0;
while continue==0
    if condata(z,1)<x
        z=z+1;
    else
        y=y+1;
        datapping(y,2:6)=condata(z-1,2:6)+((condata(z,2:6)-condata(z-
            1,2:6))*(x-condata(z-1,1))/(condata(z,1)-condata(z-1,1)));
        datapping(y,1)=x;
        x=x+inter;
        if x>4.51
            continue=1;
        end
    end
end
clear condata;
% Calculating average peaks and means
for coefficient=1:5
    meancoeff(1,coefficient)=mean(real(datapping(100:150,(coefficient+1))));
    stdevcoeff(1,coefficient)=std(real(datapping(100:150,(coefficient+1))));
end
% Saving the transient results to file
fprintf('Saving transient data...\n');
liftco=fopen(liftcoeff,'a');
fprintf(liftco,'%6.3f,%6.1f,',meancoeff(1,1),yaw);
for x=1:225
    fprintf(liftco,'%6.3f,',datapping(x,2));
end
fprintf(liftco,'\n');
fclose(liftco);
pitchco=fopen(pitchcoeff,'a');
fprintf(pitchco,'%6.3f,%6.1f,',meancoeff(1,2),yaw);
for x=1:225
    fprintf(pitchco,'%6.3f,',datapping(x,3));
end
fprintf(pitchco,'\n');
fclose(pitchco);
sideco=fopen(sidecoeff,'a');
fprintf(sideco,'%6.3f,%6.1f,',meancoeff(1,3),yaw);
for x=1:225
    fprintf(sideco,'%6.3f,',datapping(x,4));
end
fprintf(sideco,'\n');
fclose(sideco);
yawco=fopen(yawcoeff,'a');
fprintf(yawco,'%6.3f,%6.1f,',meancoeff(1,4),yaw);
for x=1:225
    fprintf(yawco,'%6.3f,',datapping(x,5));
end
fprintf(yawco,'\n');
fclose(yawco);
rollco=fopen(rollcoeff,'a');
fprintf(rollco,'%6.3f,%6.1f,',meancoeff(1,5),yaw);
for x=1:225
    fprintf(rollco,'%6.3f,',datapping(x,6));
end
fprintf(rollco,'\n');
fclose(rollco);
clear datapping;
end
end

```

Steady State Force Data Reduction of Radiused 1-Box Model

% Matlab program for analysis of steady state CROSS WIND TRACK force data written by ADChadwick November 1997

% Modified from matlab force reduction program by A R Macklin Summer 1996

clear all

pack

% Calibration matrix

dat=[0.4762 4.5943 0 0 0 0 %Newtons and Nm

0.4866 -4.5841 0 0 0 0

0 0 0.526 3.2259 0 0

0 0 0.5141 -3.3766 0 0

0 0 0 0 14.155 0

0 0 0 0 0 1];

calmax1=inv(dat);

% Counters

dragcount=1;

resfileheader=0;

currentdate=date;

% Text file that contains the data files

filenames='z:\data\roundbox\force\rbxstatforce.txt';

% Directory that the data files are kept in

dir='z:\data\roundbox\force';

sdir=size(dir,2);

% Text file to put the results data in

resultsfile='z:\data\force\static\statforc.res';

% Reads the text file that contains the filenames

fnames=fopen(filenames,'r');

repeat=0;

n=1;

while n<=36

 filen(n,:)=fscanf(fnames,'%s',1);

 n=n+1;

end

[p,q]=size(filen);

nofiles=n-1;

fprintf('\n%g files will be processed \n',nofiles);

fclose(fnames);

% Ambient temp and pressure

press=1009;

temp=16;

% Start of processing of test data. 2 files per run; 1 run, 1 windoff

for pfileno=1:nofiles/2

 % defines the full source file name

 fsourcefile=filen((2*pfileno-1),:);

 sfsourcefile=size(fsourcefile,2);

 for n=1:sdir

 sourcefile(1,n)=dir(1,n);

 end

 for n=sdir+1:sfsourcefile+sdir

 sourcefile(1,n)=fsourcefile(1,n-sdir);

 end

 fzero1file=filen((2*pfileno),:);

 sfzero1file=size(fzero1file,2);

 for n=1:sdir

 zero1file(1,n)=dir(1,n);

 end

 for n=sdir+1:sfzero1file+sdir

 zero1file(1,n)=fzero1file(1,n-sdir);

 end

 fprintf('the data file is: %s\n',sourcefile)

 fprintf('the zero file is: %s\n',zero1file)

% Reading in raw data

 sfile=fopen(sourcefile,'r');

 hdataset=fscanf(sfile,'%s',[1,2]);

 hvers=fscanf(sfile,'%s',[1,2]);

 hnumseries=fscanf(sfile,'%s',[1,2]);

 hstorage=fscanf(sfile,'%s',[1,2]);

 hsername=fscanf(sfile,'%s',[1,2]);

 hunits=fscanf(sfile,'%s',[1,2]);

 hinterval=fscanf(sfile,'%s',1);


```

timeint=fscanf(sfile,'%g',1);
hcomment=fscanf(sfile,'%s',1);
mmwater=fscanf(sfile,'%g',1);
hdata=fscanf(sfile,'%s',1);
fprintf('Header check... DATA = %s\n',hdata);
rawdata=fscanf(sfile,'%g %g %g %g %g %g',[6 inf]);
nosamp=size(rawdata,2);
fclose(sfile);
% Reading wind-off data
fprintf('Averaging zeros....\n')
z1file=fopen(zero1file,'r');
z1hdata=fscanf(z1file,'%s',[1,4]);
z1data=fscanf(z1file,'%g %g %g %g %g %g',[6 inf]);
lenz1data=size(z1data,2);
avzdata=mean(z1data);
stdevz=std(z1data);
fclose(z1file);
avzdata=avzdata;
% Subtracts wind-offs from rawdata
for m=1:6
    for n=1:nosamp
        rawdata(m,n)=rawdata(m,n)-avzdata(m);
    end
end
% Calibrating
convdata(1:6,1:nosamp)=calmax1*rawdata(1:6,1:nosamp);
clear rawdata;
% Test Data
density=1.225*press*288/(1000*(273+temp)); % Pressure in mbar, temp in degC
tunnelq=9.80665*mmwater*0.9834; %0.9834 accounts for difference in q
tunnelspeed=(2*tunnelq/density)^0.5;
viscosity=0.00017894*(288.16+110)/((273.15+temp+110)*((273.15+temp)/288.16)^1.5;
Re=density*tunnelspeed*0.2/viscosity; %Re based on square root frontal area
convdata=convdata;
% Non-dimensionalising
meanf=mean(convdata)/(tunnelq*0.04); %frontal area = 0.2*0.2 = 0.04m2
stdevf=std(convdata)/(tunnelq*0.04);
meanf(2)=meanf(2)/0.48; %pitch
meanf(4)=meanf(4)/0.48; %yaw
meanf(5)=meanf(5)/0.2; %roll
stdevf(2)=stdevf(2)/0.48;
stdevf(4)=stdevf(4)/0.48;
stdevf(5)=stdevf(5)/0.2;
clear convdata;
% Translating roll moment from body axes to groundplane
meanf(5)=meanf(5)+(meanf(3)*0.13/0.2);
% Saving results
fprintf('saving results....\n')
resfile=fopen(resultsfile,'a');
while resfileheader==0;
    fprintf(resfile,'Dataset %s processed on %s\n',filenames,currentdate);
    fprintf(resfile,'sourcefile,zerofile,ch1 zero,ch2 zero,
        ch3 zero,ch4 zero,ch5 zero,ch6 zero,');
    fprintf(resfile,'ch1d1,ch2d1,ch3d1,ch4d1,ch5d1,ch6d1,');
    fprintf(resfile,'Tunnelspeed(m/s),Tunnelq(Pa), Density(kg/m3),Re,');
    fprintf(resfile,'lift,stdev,pitch,stdev,side,stdev ,yaw,stdev,roll,stdev \n');
    resfileheader=1;
end
fprintf(resfile,'%s',fsourcefile);
fprintf(resfile,'%s',fzero1file);
fprintf(resfile,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f',avzdata);
fprintf(resfile,'%6.3f,%6.3f,%6.3f,%6.3f,%6.3f,%6.3f',stdevz);
clear stdevz;
fprintf(resfile,'%6.1f,%6.1f,%6.3f,%6.0f',tunnelspeed,tunnelq,density,Re);
for coefficient=1:5
    fprintf(resfile,'%6.3f,%6.2f',meanf(coefficient),stdevf(coefficient));
end
fprintf(resfile,'\n');
fclose(resfile);
end

```

Fortran Program to Reduce Pressure Data to Fieldview Format

```

C PROGRAM movie3d
  IMPLICIT NONE
  INTEGER i,j,k,im,jm,km,itime,itimem,itimemax,n,itimdoub
  PARAMETER (im=51,jm=21,km=21,itimem=225)
  REAL x(im,jm,km),y(im,jm,km),cp(im,jm,km,itimem),dummy
  REAL xwin(im,im),ywin(im,im),xfro(im,im),yfro(im,im),z(im,jm,km)
  REAL xlee(im,im),ylee(im,im),xmax,ymax,zmax,xmin,ymin,zmin
  CHARACTER*3 INT2CHAR,chartemp CHARACTER*60 datafile
  xmin=3.0 ymin=3.0 zmin=3.0 xmax=477.0 ymax=197.0 itimemax=225

C Read front face (also rear)
OPEN (1,FILE='front.prn',STATUS='OLD',FORM='FORMATTED')
DO i=1,jm
  DO j=1,jm
    READ(1,*) xfro(i,j),yfro(i,j)
  END DO
END DO
CLOSE (1)

C Read windward face (also top, leeward and bottom)
OPEN (1,FILE='wind.prn',STATUS='OLD',FORM='FORMATTED')
DO i=1,im
  DO j=1,jm
    READ(1,*) xwin(i,j),ywin(i,j)
  END DO
END DO
CLOSE (1)

C Now turn the faces into the fieldview model starting with Top face
j=jm
DO i=1,im
  DO k=1,km
    x(i,j,k)=xwin(i,k)
    y(i,j,k)=ymax
    z(i,j,k)=ywin(i,k)
  END DO
END DO

C Bottom face.
j=1
DO i=1,im
  DO k=1,km
    x(i,j,k)=xwin(i,k)
    y(i,j,k)=ymin
    z(i,j,k)=ywin(i,k)
  END DO
END DO

C Windward face.
k=km
DO i=1,im
  DO j=1,jm
    x(i,j,k)=xwin(i,j)
    y(i,j,k)=ywin(i,j)
    z(i,j,k)=zmax
  END DO
END DO

C Leeward face.
k=1
DO i=1,im
  DO j=1,jm
    x(i,j,k)=xwin(i,j)
    y(i,j,k)=ywin(i,j)
    z(i,j,k)=zmin
  END DO
END DO

C Front face.
i=im
DO k=1,km
  DO j=1,jm
    x(i,j,k)=xmax
    y(i,j,k)=yfro(k,j)
    z(i,j,k)=xfro(k,j)
  END DO

```

```

      END DO
C    Back face.
      i=1
      DO k=1,km
        DO j=1,jm
          x(i,j,k)=xmin
          y(i,j,k)=yfro(k,j)
          z(i,j,k)=xfro(k,j)
        END DO
      END DO
C    Now generate the rest of the grid.
      DO i=2,im-1
        DO j=2,jm-1
          DO k=2,km-1
            x(i,j,k)=240.0
            y(i,j,k)=100.0
            z(i,j,k)=100.0
          END DO
        END DO
      END DO
C    Read pressure data filename
      PRINT *, 'Name of data file?'
      READ (*,*) datafile
      OPEN (2, FILE=datafile, STATUS='OLD', FORM='FORMATTED')
C    Front face.
      i=im
      DO itime=1, itimemax
        DO k=1,km
          DO j=1,jm
            READ(2,*) cp(i,j,k,itime)
          END DO
        END DO
      END DO
C    Rear face.
      i=1
      DO itime=1, itimemax
        DO k=1,km
          DO j=1,jm
            READ(2,*) cp(i,j,k,itime)
          END DO
        END DO
      END DO
C    Windward face.
      k=1
      DO itime=1, itimemax
        DO j=1,jm
          DO i=1,im
            READ(2,*) cp(i,j,k,itime)
          END DO
        END DO
      END DO
C    Leeward face.
      k=km
      DO itime=1, itimemax
        DO j=1,jm
          DO i=1,im
            READ(2,*) cp(i,j,k,itime)
          END DO
        END DO
      END DO
C    Bottom face.
      j=1
      DO itime=1, itimemax
        DO k=1,km
          DO i=1,im
            READ(2,*) cp(i,j,k,itime)
          END DO
        END DO
      END DO
C    Top face.
      j=jm
      DO itime=1, itimemax
        DO k=1,km

```

```

        DO i=1,im
            READ(2,*) cp(i,j,k,itime)
        END DO
    END DO
    END DO
    CLOSE (2)
C   Cp for other grid points.
    DO n=1,itimemax
        DO k=2,km-1
            DO j=2,jm-1
                DO i=2,im-1
                    cp(i,j,k,n)=0.0
                END DO
            END DO
        END DO
    END DO
    PRINT *, 'Finished reading data.'
C   Output grid data in a from suitable for Fieldview.
    OPEN (3, FILE='fv.xyz', FORM='FORMATTED', STATUS='UNKNOWN')
    WRITE (3,*) im,jm,km
    WRITE (3,*) (((x(i,j,k),i=1,im),j=1,jm),k=1,km),
&      (((y(i,j,k),i=1,im),j=1,jm),k=1,km),
&      (((z(i,j,k),i=1,im),j=1,jm),k=1,km)
    CLOSE (3)
C   Output pressure data for each timestep
    dummy=1.0
    DO itime=1,itimemax
        itimdoub=2*itime
        chartemp=INT2CHAR(1000+itimdoub)
        OPEN (4, FILE='fv'//chartemp(1:4)//'.q', FORM='FORMATTED', STATUS='UNKNOWN')
        WRITE (4,*) 'fv'//chartemp(1:4)//'.q', 1000+itimdoub
        WRITE (4,*) im,jm,km
        dummy=REAL(itime)
        WRITE (4,*) dummy,dummy,dummy,dummy
        WRITE (4,*) (((cp(i,j,k,itime),i=1,im),j=1,jm),k=1,km),
&      (((dummy,i=1,im),j=1,jm),k=1,km),
&      (((dummy,i=1,im),j=1,jm),k=1,km),
&      (((dummy,i=1,im),j=1,jm),k=1,km),
&      (((dummy,i=1,im),j=1,jm),k=1,km)
        CLOSE (4)
    END DO
END
C   End of File.
INTEGER I,ic(0:9),digit,ll
CHARACTER*4 Int2char
CHARACTER*1 cdigit
REAL REALL
INTEGER M
        ic(0)=ICHAR('0')
        ic(1)=ICHAR('1')
        ic(2)=ICHAR('2')
        ic(3)=ICHAR('3')
        ic(4)=ICHAR('4')
        ic(5)=ICHAR('5')
        ic(6)=ICHAR('6')
        ic(7)=ICHAR('7')
        ic(8)=ICHAR('8')
        ic(9)=ICHAR('9')
        ll=I, m=0
        DO WHILE (ll.ge.1)
            digit=INT((0.1*REAL(ll)-ll/10)*10.0+0.5)
            cdigit=CHAR(ic(digit))
            ll=(INT(ll)-digit)/10
            cdigit=CHAR(ic(digit))
            IF (m.eq.0) THEN
                Int2char=cdigit
                m=1
            ELSE
                Int2char=cdigit//Int2char
            END IF
        END DO
    END DO
END DO

```