Dynamic Analysis of a Double Delta Wing in Free Roll

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Abstract

Wing rock is an undesirable phenomenon exhibiting limit-cycle roll oscillations that occurs on highly swept slender wings at high angles of attack. The characteristics of this motion experienced on single delta wings have been comprehensively researched and successfully controlled using various blowing techniques. The motion associated with double delta wings however is less understood and involves complex interactions from the presence of additional leading edge vortices. Research in this project focused on wind tunnel experiments to investigate the vortical flow structure acting over a 76/40° double delta wing. A series of experiments using a subsonic wind tunnel were developed to broaden the understanding of the complex flow field structure interacting with these planforms. This analysis required the design and manufacture of a new model incorporating pressure taps over the upper surface of the wing. The pressure taps were orientated along the chord of the wing in an arrangement that followed predicted vortex paths. In order to account for vortex displacement with increasing angles of attack, the paths were designed with a slight offset over either side of the wing. This arrangement provided a greater footprint over the planform to ensure that surface pressure measurements could be taken in the presence of a dynamic flow field. Unsteady surface pressure measurements were collected as the model transitioned through predetermined angles of attack with particular interest when the wing exhibited wing rock motion. Flow visualisation using laser sheet imaging was conducted to augment the analysis of vortex behaviour and to verify the pressure measurement results. The design of a special purpose pressure acquisition system demonstrated that it is possible to capture dynamic flow field behaviour over the surface of the wing. The use of this system and the data obtained from it will assist future research into the development of a suitable controller to suppress wing rock motion using a flow management technique.

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Nomenclature

LEX = leading edge extension
RASB = recessed angled spanwise blowing
Kink = the juncture on a double delta wing where the strake meets the main wing
Z plane = vertical plane on the model extending from the lower surface to the upper surface
Leeward = surface (upper) of the wing directed away from the oncoming flow
Windward = surface (lower) of the wing directed towards the oncoming flow
x/c = non dimensional chordwise reference position
Roll attractors = the roll angle around an equilibrium axis
α or AoA = angle of attack [degrees]
ϕ = roll angle [degrees]
Hz = Hertz
I Introduction

A Background

The strake/wing configuration, also known as a ‘double delta wing’, enhances the aerodynamic characteristics at high angles of attack by increasing the wings maximum lift potential and reducing drag. The single delta wing evolved by modifying traditional swept wing designs into a planform that could meet the demands of pushing aircraft into the supersonic region. These wings offer a significant aerodynamic advantage that allow them to operate at high angles of attack due to vortical lift; although they perform quite poorly during low speed manoeuvres.

The performance issues of the delta wing were significantly enhanced when designers introduced the double delta wing. The double delta wing consists of leading edge extensions forward of the main wing which gives the appearance of a ‘kink’ along the leading edges as shown in Fig.1. Forward of the kink, the leading edge extensions (LEX or strakes) are highly swept at typical angles in the order of 76-80°. The addition of leading edge extensions serves to provide a stable vortex which persists over the upper surface of the wing. The area of the wing that extends behind the kink forms the main wing that has considerably less leading edge sweep. The larger area of the main wing offers an increase in agility and performance during low speed manoeuvres. Flow separation experienced at the leading edges of the wing produce a pair of primary vortices which is shown in Fig.6. At low angles of attack, the vortices remain relatively independent of one another. As the wing increases the angle of attack, these vortices begin to interact with one another, resulting in lateral instability and limit-cycle roll oscillations known as ‘wing rock’.

B Aim

The aim of this thesis will be to develop a detailed understanding of the flow field structure acting over double delta wings. The detailed analysis will be formulated from flow visualisation techniques in conjunction with surface pressure measurements. The results from this analysis will advance the development of a suitable controller using the recessed angled spanwise blowing (RASB) technique to manipulate vortex behaviour and suppress wing rock motion.

C Scope

The scope of this project involves a series of experiments conducted in the subsonic wind tunnel. These tests will cover an array of options to develop a better understanding of the complex flow field that interacts with a double delta wing. If an understanding of the flow structure can be developed, further research will be conducted to assess the suitability of integrating pressure measurements into a controller capable of suppressing wing rock motion using RASB.

The experiments will be conducted under dynamic conditions on both single and double delta wings with the models restricted to a single degree of freedom (free-to-roll). To isolate the effects of side slip, the model will be held rigid around the yaw axis. Throughout the experiment, pressure and potentiometer data will be recorded as the angle of attack and freestream velocity are altered.

The initial tests will begin with dynamic pressure measurements whilst the wing is undergoing wing rock motion. Once the data has been collected, pressure distribution maps will be generated for further analysis. In order to substantiate these results, flow visualisation experiments will be conducted. The flow visualisations using laser sheet imaging will also assist in determining motion characteristics such as vortex position, interaction, and breakdown locations.

Pressure measurements will also be acquired whilst the RASB system is in operation to enable further analysis of the flow field in response to vortex manipulation. The use of this blowing technique has previously been demonstrated by Ong, Wong, Campbell, and England as an effective control measure.

The results obtained from this research will assist in the future development of a rule based wing rock controller.

Figure 1: Flow field on a double delta wing.
D Limitations

The characteristics of wing rock have been established as an oscillatory motion primarily in roll and yaw that arises due to the occurrence of an unstable Dutch roll mode. The Dutch roll mode involves a combination of yawing and rolling oscillations that adds further complexity to the wing’s dynamics and is outside the scope of this thesis. To simplify the analysis of this motion, the effects from sideslip will be neglected by restricting movement around the model’s yaw axis and allowing free-to-roll responses only. In addition to the rolling motion, the model will be tested at angles of attack varying between $\alpha = 0^\circ - 42^\circ$ which is the upper and lower limits of the model’s AoA mechanism. The experiments will also investigate changes in wing rock performance over a range of freestream speeds which will be limited to the wind tunnel’s maximum speed of 30 m/s.

II Project Methodology

A Requirement for the Project

The research efforts of Ong and Wong under Dr Sreenatha, have demonstrated that RSAB is capable of suppressing wing rock motion for a single delta wing. These experiments were successful due to the predictable vortex behaviour occurring over these wings.

The double delta wings however poses further additional challenges. The flow field behaviour over these wings involves additional vortices that interact with one another at high angles of attack. The end result is a wing that oscillates around discrete roll angles in a chaotic manner. Campbell and England continued the research into the wing rock phenomena on the double delta planforms, but have had limited success. One of the main challenges they faced was an incomplete understanding of the flow field behaviour leading to pressure imbalances occurring over the wing. This thesis attempts to further build upon their work by incorporating pressure taps over the upper surface of the wing. The collection of unsteady surface pressure measurements will create a broader perspective of the flow field characteristics and ultimately lead towards the development of a more robust controller.

Another important consideration for integrating pressure taps into the surface of the wing is to improve the feedback response time of the controller. All of the previous researchers described the difficulties associated with time lags that are inherent characteristics of the system. Therefore it stands to reason that in order to develop a robust controller to suppress wing rock motion, it is imperative that the flow field characteristics interacting with the wing are clearly defined. Only then can the project move towards developing a suitable controller.

B Redesign of a New Model

The initial model designed by Campbell displayed the characteristics of wing rock motion superbly. He did however note that the structural integrity of the model limited the operating pressures (60 psi) delivered to the RASB ports on the upper surface of the wing. He also suggested that additional RASB ports extending from the LEX’s as shown in Fig.2 would provide additional vortex manipulation over the area of the wing where main and strake vortices interact.

England incorporated these design changes into a second model and also reconfigured the compressed air chambers within the internal structure of the wing. By reducing the internal volume of the air chambers, the model’s response time in delivering air through the RASB ports could be improved. Unfortunately England was unable to evaluate the benefits of a reconfigured design as the wing was incapable of exhibiting wing rock motion.

Continuing on from the work conducted by Campbell and England, it was necessary to design a new model that could accommodate pressure taps. This also afforded the opportunity to incorporate suggestions recommended from previous research in this field conducted within ACME (School of Aerospace, Civil and Mechanical Engineering).

Before the development of the new model could proceed, the characteristics that were altered from Campbell’s successful design required further investigation to understand why England’s model would not initiate wing rock.

Figure 2: New model design incorporating pressure taps and RASB ports.
The mass moment of inertia around the longitudinal axis for England’s design was estimated to be $1.0 \times 10^{-3}$ kg.m$^2$. The heavier model developed by Campbell had an estimated mass moment of inertia value of $2.0 \times 10^{-3}$ kg.m$^2$. With a much lower mass moment of inertia, it is feasible that England’s model should be able to exhibit wing rock motion. The other main difference between the two models was that England’s model was constructed entirely from aluminium. The main body of Campbell’s model was also constructed from Aluminium but it contained a lower steel cover plate. The main body of each of these models was milled from an Aluminium billet which has the majority of the material remaining above geometric centre of the wing. The only conclusive result that could be achieved between the two models was that the lower steel plate redistributed the centre of mass to a more neutral position that allowed the model to rotate freely around the longitudinal axis. To test this theory, the cover plate material was altered on the new Catia model from steel to aluminium. Altering the material properties significantly changed the position of the model’s centre of mass. With the aluminium cover plate fitted to the model, the centre of mass acting in the Z plane was located at 2.301 mm. Changing the material properties to steel shifted this location up to 3.121 mm which is located closer to the geometric centre line of the attachment point located on the model (3 mm). Further testing after the new model was constructed found no noticeable difference between the use of either material as the cover plate. However adding additional weights to the central axis on the lower side of Campbell’s model did convincingly improve wing rock characteristics.

Another major design change in the new model was to incorporate pressure taps on the leeward surface of the wing. Two pressure sensor systems based on absolute and differential pressures were considered for this project. Whilst either system was capable of obtaining the results, the differential pressure transducers were selected as they are capable of achieving higher sampling rates and resolution. Initial testing of these sensors by applying a pressure step response achieved a consistent and steady rise time of approximately 10 ms (milliseconds). This translates to a sampling frequency of 100 Hz and will be sufficient in capturing the dynamic behaviour of wing rock motion that occurs around a frequency of 3 Hz.

The final design issue that required further investigation was the model’s structural integrity. The bottom cover plates on the previous designs were bonded together with a two part epoxy resin. Campbell noted that during one of his experiments, the cover plate blew off when it was operating at 60 psi. The cover plate was bonded again and the experiments continued with no further reoccurrences. The bonding process appears to be sound, however to increase the structural strength of the new model, the bottom cover plate is held secure with the inclusion of screw attachment points. The surfaces of the two mating parts can also be etched to remove surface oxides prior to the application the epoxy resin to increase the strength if required. These additional features will allow testing of the RASB system at higher operating pressures to further enhance vortex manipulation in future projects.

The technical design drawings for the new model incorporating these improvements are attached at Appendix F.

C Project Direction

The development of the pressure acquisition system required calibration tests prior to conducting experiments. Preliminary tests found that pipe lengths of up to 1.75 m (double the length used during the experiments) measured fairly consistent response times of 10 ms which will be suitable to sample dynamic surface pressures acting over the wing.

The start of wind tunnel experiments commenced with dynamic and static pressure tests on the single delta wing developed by Ong. The next phase of the experiment involved trials with the new model in preparation for further testing. Some of these tests included pressure measurement samples, model alignment, free-to-roll responses, and investigations into roll resistance created from the model’s plumbing attached to the trailing edge of the wing.

Once these preliminary tasks were completed, dynamic measurements of the flow field acting over the wing were recorded and analysed. The key indicators from this data were to identify sensitive areas of the wing or dynamic characteristics that have the potential to provide controller inputs. The determination of these parameters from the data will assist in generating rule based commands that can direct the control of RASB into the localised areas.

The next phase of testing progressed into validating the results produced from pressure distribution maps. Flow visualisations using laser sheet imagery provided the visual representation of the flow field to substantiate the experimental results. The development of further rule based commands is likely to be an iterative process that will blend between the phases of future research projects. Upon conclusion of these test phases, the data and final documentation will be correlated for submission. Research into similar projects in this field suggests that the methodology is feasible. The results produced from the research efforts of Ong, Wong, Campbell, and England have shown that the RASB technique coupled to a suitable controller can suppress the chaotic behaviour associated with wing rock. Other research conducted from Riley...
Carroll\textsuperscript{11}, Yeo\textsuperscript{12}, Kleczaj\textsuperscript{13}, and Wong\textsuperscript{14} have shown promising applications during static conditions to determine vortical behaviour and breakdown locations. To further support the tests associated with dynamic conditions, Arena and Nelson\textsuperscript{15} developed and successfully recorded surface pressure measurements using a single delta wing.

D Summary

The level of research conducted in this field appears to be mature. This project will incorporate the efforts from the individual research groups into one complete system to analyse the effects of wing rock.

The project schedule has been populated into Microsoft Project and is expected to take 38 weeks to complete. The project schedule is attached at Appendix D.

III Literature Review

A Introduction

The study of wing rock motion and the aerodynamic characteristics that surround it have captivated researchers since the 1950s. Despite extensive research in this field, the complete understanding of this phenomenon and the underlying mechanisms remain unsolved. In spite of these challenges, huge strides in controlling the motion with applications such as boundary layer manipulation, wing geometry, vortex generators, and intelligent controllers have paved the way in obtaining a partial solution.

B Wing Rock

Wing rock is classified as a self sustained oscillatory motion with increasing amplitude up to the limit cycle\textsuperscript{16}. The mode commonly applies to slender wing aircraft operating at high angles of attack and can be described by both large roll amplitudes and coupling with directional modes. This presents undesirable characteristics when an aircraft is attempting to land.

The non-linear phenomenon imparts adversely on the aircraft’s handling qualities and restricts the maximum achievable angle of attack. Despite extensive research in this field since the 1950s, the factors that contribute to wing rock are not fully understood and there exists many contradictory theories on how this behaviour occurs.

Go and Lie\textsuperscript{17} propose that wing rock can be categorised into three main scenarios; variation of damping in roll with an angle of sideslip, cubic variation of lateral derivatives with roll rate and sideslip, and the presence of aerodynamic hysteresis in a steady-state rolling moment. On the other hand, research conducted by Shah, Unnikrishnan, and Ananthkrishnan\textsuperscript{8} suggest that it is a well publicised fact that wing rock arises from an unstable Dutch roll mode where the Dutch roll eigenvalues cross over to the right side of the phase plane. The onset of wing rock can then be pre-empted by knowing the behaviour of a pair of these eigenvalues situated on the imaginary axis. Ng, Malcolm, and Lewis\textsuperscript{18} advocate that a number of aerodynamic instabilities contribute to wing rock that include; zero sideslip with asymmetric vortex lift-off from the wings or fore body, asymmetric vortex breakdown over the wings with the variation in sideslip or roll angle, static hysteresis associated with vortex breakdown and lift-off, and time or phase lag effects associated with vortex lift.

The above hypotheses predominantly relate to the motion experienced on a single delta planform; the motion over a double delta wing is however a more complicated problem.

Pelletier\textsuperscript{3} studied an 80/65° double delta wing during his research and identified various types of rolling motions, roll attractors, and critical states. He also observed different dynamic regimes that appeared to occur as a function of the angle of attack. These included damped oscillations, limit-cycle type oscillations centred around zero or non zero roll angles, and chaotic oscillations. Similar research projects conducted by Hauff and Ericsson\textsuperscript{19} also observed this behaviour.

For $\alpha < 25^\circ$, Pelletier's\textsuperscript{3} model was highly damped and there was no oscillatory motion or evidence of vortex breakdown over the wing. When his model reached $\alpha = 25^\circ$, it began to oscillate around roll angles other than zero. He also noted that this began to occur as the vortex breakdown moved over the main section of the wing. At $\alpha = 27^\circ$, Pelletier then observed that the oscillation began to increase in amplitude for all pitching angles up until $\alpha = 40^\circ$ where the amplitude began to decrease and the oscillations settled back around $\phi = 0^\circ$.

The settling down of the chaotic behaviour appeared to occur when the location of the vortex breakdown had now shifted to the leading edge kink juncture. Flow visualisations conducted after these initial tests indicated that the vortex lift off occurred between $34^\circ \leq \alpha \geq 39^\circ$ for $\phi = 0^\circ$. The sudden displacement when the vortex lifted off the surface of the wing correlated to a drop in the normal force data collected.
at \( \alpha \approx 34^\circ \). As the wing rotated through a small angle around the longitudinal axis, the windward vortex reattached to the surface of the wing while the leeward vortex did not.

The complicated flow topology interacting with the wing gives rise to critical states which is considered where discontinuities in the aerodynamic coefficient or its derivatives appear to occur as shown in Fig.3. Another example of a critical state (one that is not analytical) is represented on single delta wings. As the wing pitches through greater angles of attack, the vortex breakdown gradually moves towards the trailing edge. The critical state occurs at some point where the angle of attack is reached that causes the vortex breakdown position to jump from a position behind the trailing edge to a point that is now upstream of the trailing edge. These sudden discontinuous points between the dynamic interaction and delay resulting from vortex lift off are believed to be associated with a time lag affecting the roll rate response as the roll angle is varied. The variation between static and dynamic vortex core positions leading to a time lag is shown in Fig.4.

Gursul’s theory on the other hand appears to be slightly contradictory by postulating the following statement:

It has generally been agreed that vortex breakdown is not a necessary condition for wing rock. During Gursul’s experiments, he did not witness any vortex breakdown evident during the oscillations at the onset of motion. Ericsson who has also completed extensive research in this field, deems that the wing rock motion appears to begin when the roll damping seems to be lost and that the underlying factors that commence the motion aren’t necessarily the mechanisms that sustain it.

The proposal of several theories related to the motion of wing rock reflects the difficulties in building a complete understanding of the phenomena. The work conducted as part of this thesis will aim to build upon the current theories in the hope to strive closer to the underlying mechanisms that create this chaotic motion.

C Delta Wing Vortex Characteristics

A vortex is characterised as a mass of rapidly whirling fluid with a low pressure core. One of the more prominent examples of this action is evident from the vortices produced over slender delta wings. At moderate angles of attack, the sharp highly swept leading edges produce large adverse pressure gradients that cause the boundary layer to separate. As a result, the separated flow rolls into a pair of highly organised vortical cores over the leeward surface of the wing. The primary vortices traverse in a spanwise direction until they encounter another adverse pressure gradient and form a smaller secondary vortex as shown in Fig.5. The influence of the primary vortices on the leeward side of the wing is to impart a suction force otherwise known as vortex lift. Research conducted by Gursul suggests...
that the time averaged axial velocities generated by these vortices are roughly axisymmetric and that at
their maximum could be in the order of four to fives time the freestream velocity. This enables the boundary
layer to stay attached for a greater length of time before becoming detached as the wing orientates through
greater angles of attack.[21]

D Double Delta Wing Vortex Characteristics

The double delta wing is essentially a delta wing with a ‘kink’ in its leading edges. The kink forms the shoulder where the leading edges of the strakes (or LEX) and main wing intersect. The geometry of these wings further complicates the flow field structure due to the presence of a pair of coherent vortices produced by the strake and main wing leading edges as shown in Fig.6.

The strake vortices beyond the kink tend to remain fairly constant as they are no longer being fed energy from flow separation over the main wing. They typically move outboard and closer to the surface of the wing. The main wing vortices are more highly energised and tend to move inwards and away from the surface of the wing.[23].

Verhaagen, Jenkins, Kern, and Washburn[1] found that for $\alpha < 10^\circ$, the two vortices remained separated and hardly interacted. Beyond this angle of attack, they observed that the interaction between the two vortices became more pronounced. At $\alpha = 15^\circ$ and $\alpha = 20^\circ$, the strake vortex was observed to burst when it is passing underneath the burst wing vortex. This was believed to indicate that the breakdown of the strake vortex was causing the wing vortex to burst. The vortex trajectories with variations in angles of attack that were observed by Verhaagen[1] are shown in Fig.23a.

A number of research projects related to the vortex behaviour acting over double delta wings have been conducted within ACME at the Australian Defence Force Academy (ADFA). Whilst the research conducted by Riley[10], Carroll[11], Yeo[12], Kleczaj[13], and Wong[14] have provided valuable information relating to vortex behaviour under static situations, the interests in this project will build upon the work developed by Ong[4], Wong[5], Campbell[6], and England[7] to provide further research towards the development of a suitable controller for the dynamic behaviour involved with wing rock motion.

E Vortex Breakdown

Vortex breakdown occurs when the vortices begin to fall apart from a rapid expansion when the wing reaches a critical angle of attack. Once the vortices begin to deteriorate, the pressure distribution over the wing changes and the result is a reduction of the lift curve slope. A further increase in angle of attack from this point forward causes the breakdown location to move aft towards the trailing edge. For delta wings with a leading edge sweep greater than $75^\circ$, the maximum lift is realised at the trailing edge and the wing stalls when the breakdown location increases beyond this point. Delta wings with less leading edge sweep reach the maximum lift coefficient as the breakdown point approaches the apex and completely stalls at angles of attack when the flow has completely detached from the surface.[23]. Fig.7 shows the effects of vortex breakdown on the lift curve slope for a family of flat plate delta wings[3].

Despite extensive research into vortex behaviour, Nelson and Pelletier[3] who are research leaders in this field, point out that no one theory to date has been widely accepted.
F Control of Vortex Breakdown

In order for the modern day tactical fighters to out perform their opponents, aircraft configurations require agile platforms often operating at high angles of attack. This exposes the platforms to unstable aerodynamic conditions such as wing rock and pushes the aircraft to its outer limits of the flight envelope. This has also meant that most modern aircraft that are naturally unstable require extensive intervention from flight control computers to maintain their desired flight.

An alternative method of increasing high aerodynamic performances without mechanical manipulations is to apply passive flow control techniques. The aim here is to manipulate the boundary layer by injecting fluid into the vortex core. In doing so, the vortex circulation increases lift and delays flow field separation to augment the aircraft’s capability. Tangential, lateral, spanwise and vortex core blowing techniques have all proven successful in delaying the onset of turbulent flow.

The redesign of the new model retained the RASB technique to influence the boundary layer and will extend upon the research in this field conducted under Dr Sreenatha by Ong\(^4\), Wong\(^5\), Campbell\(^6\), and England\(^7\). This technique was first developed by Johari, Olinger, and Fitzpatrick\(^26\) as shown in Fig.8 which involved injecting the fluid from canted blowing ports that are parallel to the bevel of the leading edges. This directs the fluid in a spanwise direction from the upper surface of the wing which reduces the risk of vertically displacing the fluid. The experiment successfully delayed the turbulent flow and improved the vortex breakdown location by 15% of the wing’s chord.

G Pressure Readings

Pressure taps have been used extensively for research experiments to build dynamic and static profiles over the surface of wings. The focus in this project will be to determine where the pressure imbalances occur over the wing in order to determine a suitable rule base to be fed into a controller. Research conducted by Verhaagen et al.\(^1\), Riley\(^10\), Kleczaj\(^13\), Wong\(^14\), Barker\(^27\), and Roberts\(^28\) have shown that it is possible to collect reliable surface pressure data under static conditions. The data is invaluable to ascertain the flow field behaviour interacting with the wing.

The challenge here remains to collect pressure sensor data while the wing is free-to-roll over selected angles of attack. Arena and Nelson\(^15\) have proven these tests are possible in an experiment they conducted on a single delta wing that involved 146 spanwise pressure taps located at the 30%, 60%, and 90% chord locations. The purpose of Arena’s experiments was to correlate the position of the leading edge vortices with the model motion during wing rock to collect information related to time, roll angle, angular velocity, and rolling moment\(^3\). He then validated the data against flow visualisation imagery and concluded that his method had produced viable results.

This project will extend upon Arena’s work by integrating the RASB technique into a controller to suppress wing rock on a double delta wing.

H Flow Visualisations

Laser sheet imaging is a useful tool to give a visual representation of the dynamic flow field characteristics acting over an aerofoil. The method involves using a smoke generator to form a vaporised column of smoke that flows over the surfaces of the model. The flow path is then illuminated by a powerful argon ion laser (\(\approx 2W\)) to produce a visible light sheet over the upper surface of the model. The images from this method are then suitable for capturing on film/video for later analysis to validate experimental results.

Verhaagen et al.\(^1\) used this method to determine the location of stagnation, attachment, and separation lines under static test conditions over a range of angles of attack. Arena\(^15\) also found that this method was useful to validate the results he obtained from dynamic pressure measurements taken on a single delta model.
I Controllers

Experimental studies conducted within ADFA have shown the application of blowing techniques to be quite effective in delaying turbulent behaviour. Sreenatha and Ong developed a simple rule based controller that directed RASB inputs into a delta wing model to control wing rock. This project was later followed up by Wong who implemented a Fuzzy Logic Controller (FLC) into the system and was very successful. After successful trails on a single delta wing, Campbell and England continued the project by adapting a similar controller to a double delta wing. As discussed previously in this document, the flow field characteristics on a double delta wing are not as predictable; hence Campbell and England were only able to produce limited results.

Ruled based and fuzzy logic controllers have proven their suitability for use in this project as the input commands are usually generated from the observations made whilst collecting experimental results. Research conducted by experts in the field such as Sreenatha, Patki, and Joshi concluded that FLC’s have the ability to perform effectively even in situations where the information about the plant is inexact and the operating conditions are uncertain. The initial controller that will extend from this research project will be a simple rule based controller. If a simplified controller proves successful, future research will extend into the development of a more robust controller such as a FLC.

J Summary

This document provides a broad overview of the theoretical parameters that contribute to the chaotic non linear behaviour of wing rock on delta wing planforms. It also forms a detailed summary of the latest research conducted in field and the techniques that I will utilise to achieve the project goals.

Each distinct element in this project has been thoroughly researched previously by educational bodies globally. To the author’s knowledge, the integration of all these individual elements into a complete system to control wing rock has not been done before.

IV Experimental Setup

A Introduction

Experiments for this project were conducted in the low turbulence subsonic wind tunnel located in the aeronautical laboratory situated within ACME. Investigations into the dynamic flow field behaviour involved the configuration of experimental equipment to analyse three main areas; free-to-roll response, pressure measurements, and flow visualisation. Pressure measurements were captured using a data acquisition module coupled to a series of pressure taps flush mounted on the upper surface of the wing. In order to validate the readings taken from pressure measurements, flow visualisation was also conducted using laser sheet imaging.

Whilst the phenomena of wing rock strongly correlated to high angles of attack, the data was assessed over the entire test envelope covering the region $\alpha = 0^\circ - 42^\circ$. Testing over this region would enable a detailed analysis of the flow field behaviour for both pre and post wing rock motion.

B Equipment

Most of the equipment required for this project was assessable from past research efforts within ACME. However due to the uniqueness of this project, several modifications were required to either enhance or extract the final results. Some of these modifications included, the design of a new model, the addition of a glass wall in the wind tunnel, reconfigured laser setup, motorised AoA mechanism, and the implementation of a high volume smoke delivery system. These modifications will be discussed in more detail in the applicable sections to follow.

C Wind Tunnel

The wind tunnel used for these experiments is an open circuit low turbulence subsonic wind tunnel capable of generating freestream speeds ($v_\infty$) up to 30 m/s. The square test section is 457 mm x 457 mm and extends over a length of 910 mm. The wooden roof of the forward test section was modified to accommodate a glass wall measuring 430 mm x 1200 mm. The main purpose for this alteration was to give greater flexibility to laser trajectories penetrating into the tunnel and extending over the model. This also provided an additional benefit of another viewing window for recording/observing experimental results. Laser configurations conducted prior to this modification relied on a small opening cut into the top wall of the tunnel. This also meant that the laser path entering the tunnel was limited in its orientation of alternative planes to achieve a variety of laser sheet configurations.
The addition of a glass wall at the top of the tunnel also allowed for a topographic perspective to view vortex interaction with the wing whilst it was undergoing wing rock motion. Viewing this motion in past experiments was only available through side windows which obscured the flow field behaviour when the model was operating at high angles of attack. A schematic diagram displaying the modified wind tunnel configuration is provided at Appendix I.

D Model Mount Assembly

The wind tunnel configuration shown in Fig.9 details the model’s mounting mechanism consisting of a base plate, stand off fixture, free-to-roll mount, and an adjusting mechanism that allows the model to pitch through angles of up to \( \alpha = 42^\circ \). The base plate is housed in the wind tunnel’s floor and is held secure by two mounting clamps. The adjusting mechanism passes through the base plate to allow for external adjustments to the AoA whilst the tunnel is in operation. The initial configuration of the adjusting mechanism altered the pitch through the use of a screw jack mounted centrally through the base plate interconnecting with the stand off linkages. This device was later modified by replacing the manual winding mechanism with a 24V DC Motor by coupling it directly to the internal shaft. The semi automatic operation gave greater freedom to observe the flow field behaviour acting over the wing whilst it was in motion. The stand off situated in the lower section of the AoA mechanism also ensures that the model is supported correctly in laminar flow so that additional turbulence created by the tunnel’s walls does not interfere with the flow.

The free-to-roll mount is a machined aluminium block that houses a voltage dividing potentiometer, RSAB plumbing, low friction bearing, and a central shaft that couples the model to the mechanism. The potentiometer is configured so that at wings level, the resistance measured is zero ohms. Roll movement to the starboard side measures positive resistances and negative values are indicated for movement to the port side. Resistance measurements are then converted using a sensitivity calculated for known angles which represents the model’s roll attitude during testing. A detailed schematic drawing displaying the AoA mechanism is attached at Appendix J.

E Double Delta Model

The design of a new model incorporated 28 pressure taps and a series of RSAB ports situated over the upper surface of the wing. The orientation and position of these features can be seen in more detail in the technical drawings attached at Appendix F. The configuration of these paths were derived from past research\(^1,3,10,12\) that published their findings using models of similar geometry to those developed within ACME by Campbell\(^6\) and England\(^7\).

Within the internal structure of the model, four air chambers receive compressed air (\( \approx 60 \) psi) through the model’s plumbing and direct it through the RASB ports situated on the upper surface of the wing. An injection of compressed air through these ports manipulates the flow behaviour of the vortices in a manner to control a desired orientation of the wing.

The initial pressure measurement tests were conducted with a bare aluminium finish to ensure that pressure taps were free from congestion. The model and free-to-roll mount were later painted in a matt black finish for the next phase of testing involving flow visualisation. Painting these surfaces matt black served two fold; to reduce the reflected laser scatter during flow visualisation, and to provide wing reference markers over the upper surface of the wing. The reference markers were produced by masking the model with 1.5 mm tape every 15 mm. The final result produced \( x/c \) markers which represent a chordwise position along the wing at intervals of \( x/c = 0.5 \) as shown in Fig.10.

Figure 9: Wind tunnel and model configuration.

Figure 10: Double delta wing showing x/c markers.
F Pressure Acquisition System

The pressure acquisition system detailed in Fig. 11 contains 24 differential pressure transducers coupled to a National Instruments SCXI-1600 USB data acquisition (DAQ) module. The Honeywell piezoresistive pressure transducers were calibrated over a range of temperatures using a pressure calibrator. This data developed a sensitivity for the transducers so that for a selected temperature, the measured voltages could be converted to pressure readings for further analysis. The sensors were soldered onto three separate circuit boards with the shielded cables clamped rigid and secured. In order to reduce any electrical interference (noise), the cables connecting the pressure sensors to the DAQ module were shielded and kept to a minimal length. Likewise the flexible 1.2 mm diameter Teflon pressure tap pipes were also kept to the smallest length possible (≈ 80 cm) and were selected for its low volume change characteristics under pressure.

The DAQ module features a 16 bit analogue to digital converter (ADC) that conditions the incoming analogue signals. These signals are then amplified and processed through Labview software which makes the information available by writing it to selected data files. The National Instruments (NI) chassis accommodates up to three data acquisition cards capable of handling eight channels per card. A total of 24 channels from this system were taken up by the free-to-roll potentiometer and twenty three pressure taps.

Pressure measurements were taken over test speeds of 15 m/s, 20 m/s, 25 m/s, 30 m/s. Thompson noted that vortex trajectories on delta planforms displace only slightly with variations of Reynolds numbers (Re#) tested below values of $1 \times 10^5$. Research conducted by O’Neil et al. tested Reynolds numbers beyond $1 \times 10^5$ and found that vortex breakdown as well as surface and force results to be virtually independent of the Reynolds number. Nelson, Pelletier, and Erickson also conclude that the flow features are usually independent of the Reynolds number. Bearing these considerations in mind, the wind tunnel test speed of 25 m/s (Re# ≈ $4.73 \times 10^5$) was selected as it exhibited the best characteristics of wing rock motion.

G Flow Visualisation

The Laser sheet imaging method shown in Fig. 12 was selected to conduct flow visualisation experiments. This technique involves injecting smoke into the freestream flow upstream of the model. The smoke particles are then carried away along the stream lines and pass over the model. A high power laser beam is then transformed into a sheet through a series of optics to highlight the characteristics of the flow field interacting with the wing.

The initial collimated beam of light produced by the Lexel argon ion laser is approximately 1.5 mm in diameter. While the beam in this form is intense, it would be inadequate to produce effective results. Following the path provided in Fig.12, the initial beam leaving the laser passes through a cylindrical lens. The purpose of this optical lens is to transform the beam into a laser sheet. The sheet then passes through a 45° mirror which directs the sheet down towards the roof of the tunnel.

Although the beam is now in the required ‘sheet’ form, it doesn’t provide enough coverage over the width of the model to highlight the entire flow field. To increase the width of the sheet, it is necessary to involve further optics.

The beam is now reflected upward from a 100 mm diameter mirror to much larger mirror mounted at the top of the support frame. The beam is then reflected off the 200 mm diameter mirror and directed towards the model where it now is capable of illuminating the width of the model.
The delivery of smoke was provided through the use of Rosco 1500 fog machine which is capable of delivering enough smoke into the flow to ensure coverage over the entire model. The machine uses a 'fog oil' which is an aqueous glycol solution. A separate delivery system which utilised a one inch stand pipe mounted to the top of the tunnel had to be manufactured to provide the release of smoke into the system.

H Summary

The experimental setup described in this chapter highlighted the reasoning for several modifications for this project. The experimental procedures also outlined the equipment required to achieve the projects goals. All of the experiments were conducted in the low turbulence wind tunnel involving test equipment that analysed the flow field behaviour over a range of freestream speeds and angles of attack. The results for these test parameters will be discussed in more detail in the following chapters.

V Free to Roll Results

A Introduction

Free-to-roll tests capture the wing’s roll motion so that under the influence of a dynamic flow field, surface pressure measurements acquired in parallel can develop a complete time history of the test envelope. The roll history also forms the primary feedback signal into the controller to augment RASB air to suppress any uncharacteristic wing rock behaviour. Whilst research that preceded this project was focused on the models response to RASB, the data in these experiments assisted in the understanding of pressure and vortex imbalances creating instability over the wing.

Figure 13: Roll angle behaviour over test envelope (a) Dynamic time history, (b) Roll attractors for $v_\infty = 25$ m/s, (c) Wing rock limit cycle for $\alpha = 37^\circ$, (d) Roll attractors for various freestream speeds, $v_\infty = 15, 20, 25, 30$ m/s.
B Roll Characteristics of a Double Delta Wing

The alteration of the flow field characteristics due to wing rock motion plays an important role in the understanding of vortex behaviour. Double delta wings exhibiting these motions have been described as chaotic manoeuvres that build up to limit cycle oscillations. Limit cycle behaviour illustrated in Fig.13c was observed in the analysis of the data during all wing rock regions represented in Fig.13a.

Nelson and Pelletier\textsuperscript{3} observed that with increasing angles of attack, these planforms establish static and dynamic roll attractors centred on zero and non-zero roll angles. Experiments conducted on the double delta model displayed the development of roll attractors over the entire test envelope. Figures 13b and 13d highlight the establishment of these roll attractors forming around both zero and non zero roll angles. Further testing revealed that for different freestream velocities, the maximum roll angle achieved was very similar in all test cases. Additionally the point where the maximum amplitude was attained also occurred around the same AoA ($\alpha \approx 27^\circ$). Arena\textsuperscript{3} also observed during his experiments that the maximum roll angle was achieved at approximately $\alpha = 28^\circ$. These results also correlate well with the values determined by Campbell\textsuperscript{6} during his experiments.

As the AoA of the wing increases from $\alpha = 0^\circ$, the flow field interaction begins to create a positive roll angle causing the starboard wing to lower. At $\alpha = 14^\circ$, the starboard wing experienced a negative roll angle which reduced the starboard displacement unexpectedly by approximately $\phi = 12^\circ$. Advancing to $\alpha = 15^\circ$ continued the positive displacement of the starboard wing again as it approached the first minor wing rock region situated between $\alpha = 23 - 28^\circ$. In this region, the wing reached a maximum displacement of $\phi \approx 47^\circ$ and saw the formation of a roll attractor that created the wing to oscillate around $\phi \approx 41^\circ$.

Beyond this region, the wing’s roll angle decays rapidly and the oscillatory motion associated with wing rock becomes gradually suppressed. At $\alpha = 33^\circ$, the wing sharply returns to wings level and establishes a new roll attractor around $\phi = 0^\circ$. Further AoA increases from this point causes small unsteady chaotic fluctuations before reaching a very strong wing rock region at $\alpha = 37^\circ$. At this AoA, the wing experiences chaotic oscillations as a result of wing rock motion that build up into limit cycle oscillations as illustrated in Fig.13c. These limit cycle oscillations remain persistent right up to the end of the test envelope ($\alpha = 42^\circ$ - the upper limit of the AoA mechanism) where the wing shows no signs of wing rock suppression.

Analysis of the test data could not explain the underlying mechanism behind the gradual roll towards the starboard side of the wing. Likewise, the peculiar rise of the starboard wing at $\alpha = 14^\circ$ could not also be explained. It is interesting to note that whilst the model favoured a drop to the starboard side throughout testing, there were a few occasions where the model would bank to the port side. Additionally if the model was forced to the port side, it showed no intention to roll back to the starboard side and all motions including wing rock motion behaved identically to those of the starboard side.

The behaviour may be the result of ‘wing drop’ or ‘heavy wing’ which is discussed in more detail by Nelson and Pelletier\textsuperscript{3}. Both these aerodynamic phenomena’s have been witnessed with fighter aircraft and whilst not completely understood are believed to be the result from rolling moments created from asymmetric wing stall\textsuperscript{5}. This behaviour was also observed by predecessors of this research project Campbell\textsuperscript{6} and England\textsuperscript{7}. One explanation to this behaviour may be that the flow field characteristics are developed as a function of the ACME wind tunnel, model geometry, and test equipment since these components have been reused throughout the wing rock projects.

C Free Roll Restrictions

The models free-to-roll mechanism relies on a low friction bearing to promote free motion as much as possible. Arena and Nelson\textsuperscript{15} in similar tests on a single delta wing that used an air bearing spindle to reduce the rolling resistance of the model. Further reduction in roll resistance was achieved by building up a time history of the data through a series of runs using only two pressure sensors at a time. This test procedure proved feasible in part due to the nature of single delta wings having repeatable flow field behaviour. Double delta wings on the other hand reflect additional complexities with the flow field characteristics interacting with the wing and it is not possible to overlay the results to develop correlated data maps.

Therefore the penalty associated with this form of testing meant that the plumbing attached to the rear of the model would provide additional roll resistance and restrict free roll motion.

In order to gain an appreciation of the restricted free motion during testing, a series of tests were performed over selected freestream velocities with and without the presence of system plumbing. The time history from these tests were analysed by producing power spectral density graphs using Fourier’s Transform shown in Fig.14. This enabled an assessment of wing rock frequencies to quantify the effects of roll resistance created by the attached plumbing. An assessment from the data shown in Fig.14a illustrates the reduction of wing rock frequencies with the restriction of pipes attached over the selected test velocities. The results shown in Fig.14b found that at 25 m/s the unrestricted wing rock frequency of 2.588 Hz was only altered
slightly to 2.539 Hz with the pipes fitted. Therefore this test velocity was selected to conduct the next phase of experiments which involved the collection of unsteady surface pressure measurements.

![Graph showing wing rock component frequencies for various freestream velocities, \( \alpha = 37^\circ \)](image)

Figure 14: Wing rock frequency, \( \alpha = 37^\circ \), (a) No pipes fitted, (b) Frequency variation with pipes fitted for \( V_\infty = 25 \text{ m/s} \).

**D Summary**

This chapter described the additional roll characteristics experienced by a double delta wing that makes the analysis of the flow field characteristics difficult. Future analysis of the results is also made difficult with the limited knowledge on the understanding of the vortex interactions causing unpredictable results.

Further challenges are also presented due to the chaotic nature of the flow field. A chaotic flow field limits the options of reducing roll restrictions by building the data up over a series of runs involving less pressure tap piping. However the test setup aimed to limit these restrictions as much as possible which still provides a method that can extract meaningful results.

**VI Flow Visualisation Results**

**A Introduction**

The main purpose behind the flow visualisation experiments were to validate the measured data and observe the behaviour of the vortex interaction during wing rock motion. This method proved invaluable to explain unusual results and to visual the displacement of the vortex paths as the roll attractors formed with increasing AoA.

The best results were achieved using a high volume smoke delivery system in order to gain full coverage over the model. This ensured that the laser sheet illuminated the entire flow field occurring over the upper surface of the wing. The following angles of attack, \( \alpha = 0^\circ, 5^\circ, 10^\circ, 15^\circ, 23^\circ, 28^\circ, 33^\circ, 37^\circ \), were identified as candidates for closer inspection based on the fact they displayed interesting or unusual behaviour.

The flow visualisation results also indicated that the predicted paths of the vortices were not always present over the pressure taps which made the deciphering of the data an arduous task. In some regions of the test envelope, the data was found to be invalid as the vortex paths were not always present over their predicted locations. In order to extract some meaningful conclusions from the results, flow visualisation enabled the determination of vortex trajectories, breakdown locations, and vortex interaction.

The details of flow visualisation over the pressure taps will be discussed in more detail in the next chapter of this document. In this section, the focus will be to explain the vortex behaviour observed throughout testing which will provide further insight into the difficulties uncovered during the analysis of the results.

**B Visualised Vortex Behaviour**

At \( \alpha = 0^\circ \), the wing demonstrated that it was very stable and balanced. The flow field acting over the leeward surface of the wing did not show any evidence that the formations of the strake or main vortices had developed from the leading edges. This contradicts observations made by Klczaj\textsuperscript{13} who noticed that vortices were present even at \( \alpha = 0^\circ \) at a freestream speed of 8m/s. This would indicate that the vortices
were present, however any visual indication were most likely to be dispersed due to a much higher wind tunnel test speed of 25 m/s.

At $\alpha = 5^\circ$, small weak vortices are evident that commence at the nose of the wing and grow to approximately the height of 1 cm by the time the flow reaches the kink. The strake vortices persist uninterrupted over the main wing and increase in size as they approach the trailing edge. The laser configuration at this angle of attack allowed the illumination of the flow field slightly beyond the trailing edge which revealed that strake vortices were still strong and had not broken down.

The main vortices generated on the other hand were weak and dispersed indicating premature vortex breakdown or an absence of flow energy produced from shear over the wing. At $x/c = 0.75$, visibility of the main vortices on either wing were so frail that it was hard to identify any further vortex flow. The vortex paths between the strake and main vortices where they both coexist, showed no signs of interaction between them which accounts for very little instability of the wing. Whilst the strake vortices remain well defined and circular in shape over the entire chord of the wing, it’s interesting to note that the main vortices appear to elongate or stretch in a spanwise direction towards the centre of the wing until they breakdown. The vortex behaviour produced over the leading edge extensions and the main wing are shown in Fig.15.

At $\alpha = 10^\circ$, the strake vortices have become stronger, remaining well defined and grow in size as they approach the trailing edge. It is difficult to see the behaviour beyond the trailing edge due to the limitations of the laser configuration at this angle of attack.

The main vortices increase in size after the kink and have expanded to the same height as the strake vortices at $x/c = 0.8$. The vortices continue to grow slightly in height down stream towards the trailing edge. During this progression, the strake vortices remain circular in shape whilst the main vortices have stretched in a spanwise direction to three times the girth of the strakes. Whilst the density of all vortices has decreased indicating higher pressures, the density of the main vortices has significantly decreased. The reduction in main wing vortical strength is responsible for the formation of higher pressures on the outer portions of the wing. It appears that the dissipation of the main vortex may be the result of the more powerful strake vortices entraining much of the flow.

Figure 15: Vortices developed at $\alpha = 5^\circ$, (a) Rear main wing $x/c = 0.9$, (b) Mid main wing $x/c = 0.6$, (c) Front strake $x/c = 0.45$. 
There was also evidence that the main vortex on the port side was stronger than that of the starboard side. Whilst it is unclear why this may be the case, it would explain why the starboard wing gradually lowers as a result of a moment imbalance created from disproportionate pressures acting over the wing.

The strake and main vortices remain separated up until $x/c = 0.9$ where they begin to butt up against each other but still contain their distinct features with little interaction. At $x/c = 0.95$, the main wing vortices have burst whilst the strakes vortices possess a well defined low pressure core until they reach the trailing edge.

Approaching $\alpha = 15^\circ$, the peculiar behaviour of a roll attractor forming increases moderately until $\alpha = 14^\circ$. At this AoA, the starboard wing reverses the trend by significantly rising approximately $\phi = 12^\circ$.

Beyond $\alpha = 14^\circ$, the starboard wing continues to drop again and maintains this downward trend as the angle of attack is further increased.

It is extremely difficult to observe what may be the leading influence that causes the wing to behave in this manner. The strake vortices around $\alpha = 14^\circ$ are very strong and over the strake section of the wing they sit upright and proud as demonstrated in Fig.16c. The port strake vortex in this region sits slightly higher away from the surface of the wing than the starboard side. The vortex is also situated right against the leading edge whilst the starboard strake has moved slightly inboard which contributes to unbalanced forces interacting with the wing.

Beyond the kink, the port strake vortex is stronger and is perched more upright than starboard side. At $x/c = 0.75$, the port side vortices are of equal size and although they are still joined together, they don’t appear to be interacting with one another. At $x/c = 0.8$ both port vortices have consolidated to a similar shape and size. Extending beyond this point, the port main vortex increases in size and elongates slightly as it traverses towards the trailing edge. At the trailing edge, the frail vortex displays an intermittent low pressure core which demonstrates that it is on the verge of vortex breakdown. The strake vortex on the other hand has decreased slightly in size at the trailing edge but still displays a solid vortical structure. Evidence still suggests that the strake vortex continues to extract flow energy from the adjacent main vortex. This behaviour sees the strake vortices amplify in strength and drawn closer to the surface of the wing. Likewise, the main vortex is now sitting slightly higher off the wing which correlates with observations witnessed by Nelson and Pelletier$^3$.

On starboard side of the wing, both vortices are the same height and join at $x/c = 0.75$ where they are clearly displaying signs of a low density vortical structure which is illustrated in Fig.16a. At $x/c = 0.85$, the starboard main vortex loses definition entirely in the low pressure core and the dispersed flow is an indication of a burst vortex. At $x/c = 0.9$ the strake and main vortex have completely merged into a single
low density mist that spreads across the entire span of the starboard wing and doubled in height as shown in Fig.16a. The flow conditions evident on the starboard wing are obviously contributing very little to lift which ensures that the wing will remain lower once an instability initiates roll in this direction.

It was interesting to note that due to the constant roll angle present on the starboard wing, the flow field conditions ensured that vortex breakdown was delayed on the port side of the wing whilst causing premature breakdown on the starboard side. Obviously this is due to the roll attractor providing favourable flow field conditions that strengthen the vortices on the port wing which are not seen in static experiments such as those conducted by Verhaagen et al.\textsuperscript{1}.

At $\alpha = 23^\circ$, the wing enters the initial wing rock region where the motion commences in sporadic and chaotic bursts. The wing also reaches its greatest average roll angle of $\phi = 44^\circ$ where wing rock motion oscillates in equilibrium around this roll attractor.

The stout vortices created from the leading edge extensions now appear to exhibit different characteristics which are detailed in Fig.17. The port strake vortex at this angle of attack has strengthened even further which is clearly evident from a much larger low pressure core. The vortex also sits more upright than the same vortex on the starboard side and has begun to move further away from the surface of the wing.

Beyond the kink, the port main and strake vortices commence to butt up against each other and reach a similar height at $x/c = 0.8$. At this location, both port vortices are showing signs of detached flow and moderate interactions with each other. The main vortex continues to expand as it approaches the trailing edge, whilst the strake vortex shrinks slightly. At the trailing edge, both vortices have detached even further from the surface of the wing with the main vortex sitting higher and swirling down on top of the strake vortex.

Fig.18 represents a third vortex generated from the port main wing that begins to emerge at $x/c = 0.65$. This appears to be a secondary vortex as detailed in Fig.5 which are tertiary formations produced from the presence of the primary vortices. Secondary vortices are generated when the flow from the main vortex swirls completely back upon itself where it once again meets the shear wall. The flow is not strong enough to penetrate the shear wall and is directed back towards the surface of the wing and reattaches with a rotation that opposes the motion of the primary vortices.

Whilst the secondary vortex never showed any signs of a low pressure core, the density in the flow was considerably elevated which appeared to dominate the behaviour of the main vortex. The secondary vortex also grew in size down stream along the wing and nestled under the main vortex forcing it to sit higher off the surface. Figure 19: Vortices developed at $\alpha = 33^\circ$, (a) Rear main wing $x/c = 0.9$, (b) Mid main wing $x/c = 0.6$, (c) Front strake $x/c = 0.45$. 

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the surface of the wing. Interestingly the main vortex now appears to extract flow energy from the strake vortex and dominates the behaviour over the wing.

Despite a more intense flow structure that has developed on the port side of the wing, the wing still manages to undergo wing rock motion overriding the strong force imbalances reacting with the wing.

Evidence of the secondary vortex was observed to persist over the range of $\alpha = 23^\circ$ to $\alpha = 33^\circ$ where the wings return back to a level orientation. The influence of this secondary vortex also presented the only time where the strake vortices were seen to breakdown before the main vortices as shown in Fig.23c. These observations would suggest that the more dominant vortex acting over the surface of the wing extracts additional flow energy from the weaker vortices surrounding it. The follow on effect from this dominant behaviour leads to premature vortex breakdown of the weaker vortices.

At $\alpha = 28^\circ$, the average roll angle continues to decay gradually back towards wings level. This angle of attack also provides the upper boundary of the initial wing rock region.

The flow over the forward strake section of the wing still behaves in a similar manner to that at $\alpha = 23^\circ$ with the exception that both strake vortices have increased in size and now have much larger low pressure cores.

Over the main section of the wing, it is even more evident now that the port vortices have become further detached from the surface of the wing. The strake vortex is superior in strength and sits considerably higher than the main vortex until it reaches $x/c = 0.8$. Beyond this point, the flow between the two port vortices’ begins interacting with one another. Whilst the main vortex remains defined up to the trailing edge, the strake vortex appears and disappears in harmonics with the oscillations of the wing.

The main vortex flowing past the trailing edge of the wing was also noticed to still be intact with faint signs of a diminished low pressure core. The presence and behaviour of the secondary vortex is still evident at this angle of attack and behaves in a similar manner as the observations discussed for $\alpha = 23^\circ$.

At $\alpha = 33^\circ$, the planform returns to a wings level equilibrium and continues to experience small unsteady chaotic fluctuations that do not develop into sustained wing rock oscillations. Despite careful observations in this region and the extensive review of video footage, the exact nature causing a shift in the dynamics

![Figure 20](image1.png)

**Figure 20:** Vortices developed over the strake section, $\alpha = 37^\circ$, $x/c = 0.5$ (a) Roll to starboard side, (b) Wings level, (c) Roll to port side.

![Figure 21](image2.png)

**Figure 21:** Vortices developed over the main wing section, $\alpha = 37^\circ$, $x/c = 0.65$ (a) Roll to starboard side, (b) Wings level, (c) Roll to port side.
Over the strake section of the wing, both strake vortices shown in Fig.19c are tight and strong but are also significantly larger than the previous angles of attack. However there appears to be slightly more strength in the port vortices which may explain why the wing tends to bank starboard when unsettled. Furthermore, the starboard side vortices are more prone to losing the low pressure cores with wing rock oscillations which sees the majority of unsteady flow increase the amplitude on this side of the wing.

Past the kink, the main vortices sit off the surface of the wing with the much smaller main vortices forming below and adjacent to them. The vortices continue to expand to double the size seen previously for any other angle of attack although the strakes still sit higher off the wing and dominate in this region. The interaction between the main and strake vortices appears very active from the point where they merge (x/c = 0.8) which creates intermittent instabilities over the wing.

At $\alpha = 37^\circ$, the wing enters a region where very strong wing rock oscillations are present. These oscillations were present over the remainder of the test envelope extending up to the limit of $\alpha = 42^\circ$. The onset of this motion appears to correlate with vortex breakdown reaching the kink of the wing. Pelletier also observed this behaviour in experiments he conducted on 80/65$^\circ$ double delta wing. Although vortex breakdown was observed to commence as it approached the kink of the wing, the vortical core structure containing a low pressure core would re-establish momentarily as the wing moved upwards on either side. The vortices would then burst and experience breakdown as the wing lowered towards a downward orientation.

Fig.20 represents a closer examination of the vortices acting over the strake section of the planform whilst undergoing wing rock motion. Commencing from wings level ($\phi = 0^\circ$), as the starboard wing lowers, the starboard vortex would move further inboard and closer to the surface of the wing. The port vortex on the upward moving wing would move outboard and further off the surface of the wing. As the starboard wing rotated towards an upward orientation, the behaviour was reversed for the respective wing. This interchange of flow field behaviour creates a loss of roll damping that leads to axisymmetric imbalances. Once these parameters are set in motion, wing rock is established and leads to limit cycle oscillatory motion.

Over the main section of the planform, the strake vortices sit higher off the wing than the main vortices. At x/c = 0.75, the vortices on each wing merge and immediately begin to interact with one another; creating a loss of further vortex definition. The strake vortices have also expanded quite considerably taking up three quarters of the wing span leaving only a small region of the wing for the main vortices to form.

Wing rock motion over the main section of the wing reacts in a similar manner to the strake section which is illustrated in Fig.21. However with an additional pair of coherent vortices in play, the motion does differ slightly. The vertical displacement of the strake vortex on the upward moving wing appears to be exaggerated due to the augmentation provided by the main wing vortex as it slides underneath it. This prevents any vertical displacement of the main wing vortex as it is now held firm on the surface of the wing due to the strake vortex sitting above it. Both strake and main vortices on the lower wing still move inboard and closer to the surface of the wing but appear to burst as the two vortices are forced together. As the wing rotates to the opposite side, the motion is reversed. The further augmentation of vertical displacement acting over the main section of the wing increases the time lag effects from displacement to reattachment of the vortices to the wing. It is possible that this may be the reason why double delta wings experiences greater chaotic non linear motion than that of a single delta wing.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{vortex-breakdown-locations.png}
\caption{Vortex breakdown locations for $V_\infty = 25$ m/s, (a) Breakdown for strake vortices, (b) Breakdown for main vortices.}
\end{figure}
C Vortex Breakdown Locations

The formation of a roll attractor with increased angle of attack, significantly altered the behaviour of vortex breakdown over the wing. The traditional behaviour of these vortices on a single delta wing sees vortex breakdown move upstream with increasing angles of attack. For low angles of attack, vortex breakdown occurs downstream of the trailing edge. Moderate increases to the angle of attack sees vortex breakdown occurring over the wing. At some critical angle, wing rock motion is initiated and axisymmetric vortex breakdown is a contributing factor to sustain oscillatory motion.

Fig. 22 indicates the location of vortex breakdown between the strake and main vortices on either side of the wing. Axisymmetric vortex breakdown leads to disproportionate forces interacting with the wing; generating a roll moment and instability of the planform. This phenomena whilst not the only contributor to oscillatory instabilities, presents significant challenges to suppress wing rock motion. Herein lies the aim of the RASB technique to provide vortex manipulation and delay the breakdown of the vortices.

Both graphs shown in Fig.22 highlight the asymmetric characteristics that develop from the presence of a roll attractor. A comparison of the same vortices on either side of the wing displays the magnitude of these imbalances. The spread between the two main vortices shown in Fig.22b magnifies the problem. These vortices provide a force with a greater lever arm. Hence any imbalance of force produced from the main vortices will amplify and dominate the results.

D Summary

This chapter detailed the visualised behaviour of many flow field characteristics. Roll attractors were shown to significantly alter the flow field conditions; adding to the complex and chaotic behaviour experienced on double delta wings. Research in this area by other institutional bodies appears limited and made it difficult to compare the results. Research into static cases on the other hand appears to be more mature. For low angles of attack, the results in this project could be considered static and compare well with the findings published from these researchers.

It was disappointing that some of the peculiar results that were witnessed could find no conclusive results. Further investigations into the gradual roll of the model as the angle of attack is increased would provide beneficial knowledge leading towards the development of a controller to suppress wing rock motion.

VII Surface Pressure Measurement Results

A Introduction

The pressure measurements involved 23 pressure taps distributed over the surface of wing to capture the dynamics of the vortex flow paths. The pressure taps were constructed in a configuration that represented typical vortex paths observed by a number of research bodies using a host of different experimental techniques. To allow for the slight variations in vortex displacement throughout testing, the main and strake vortex paths were arranged with a slight offset on either side of the wing. The arrangement of these pathways is provided in more detail in Appendix F (technical drawings). The reasoning behind this decision was to provide a larger footprint over the wing in order to ensure measurements could be extracted as vortex paths altered slightly with variations in AoA.

Unsteady surface pressure measurements conducted during testing were captured at 100 Hz and acquired for 20 seconds to ensure that the flow field was at a steady state. A time exposure of two seconds from this data was extracted for detailed analysis. This time frame contained 200 samples that captured pressure measurements as the wing rotated through approximately 6 complete wing rock oscillations.

The original design of the model had the provision to connect 28 pressure taps over the upper surface of the wing. However no equipment was available within ACME that could provide enough channels to meet this specification. Attempts to purchase this equipment proved cost prohibitive and hence a compromise of equipment capable of running 24 channels was selected. An alternative solution to over come these constraints would have been to build up the data over a number of runs. However this solution was not possible as the chaotic random behaviour of double delta wings would produce uncorrelated data that would be meaningless to compare. Therefore five pressure taps ranked with a lower priority were not utilised throughout the experiments.

B Validity of Pressure Tap Measurements

The initial analysis of the data showed some very confusing results. At times the data represented the expected behaviour and then the trend would become incoherent. Further flow visualisation testing was
conducted in an attempt to identify the vortex behaviour above the pressure taps. Flow visualisation maps shown in Fig.23 were produced to identify the relationship between the pressure taps and vortex paths. The observations quickly identified the cause of abnormal readings created from vortices taking unexpected paths. This meant that vortices in certain regions of the wing were not present or above the pressure taps giving uncharacteristic readings. Additionally some pressure taps were measuring the edge of a vortex that meant that the flow was directed down upon them. In these situations, the pressure tap acted like a pitot probe and measured a head of pressure instead of static pressure.

The main cause of vortex displacement over the pressure taps was due to the formation of non centred roll attractors as the model increased AoA. Pelletier\textsuperscript{1}, Hanff\textsuperscript{19}, and Ericsson\textsuperscript{22} also discovered the existence of wing rock motion around non zero roll attractors. However no detailed research into the severity of vortex displacement under dynamic environments appears to have been published. Gursul\textsuperscript{21} also concluded in his studies surrounding vortex flows over slender wings that;

Vortex wandering remains a problem in characterisation of leading edge vortices. The relationship between shear layer instabilities and vortex wandering requires further study.

In lieu of meaningful results over the entire test field, flow visualisation maps did offer areas where the vortical behaviour could provide dynamic results over the wing. At this point of the analysis, the focus shifted more towards examining valid data in terms of gauging the ability of the pressure acquisition system to capture dynamic results. If this system can successfully achieve this goal, it would prove its usefulness in continuing research in this field.

The results indicated on Fig.23b represent that vortex paths up until \(\alpha \approx 10^\circ\) follow a reliable path over all of the pressure taps. The vortex paths on these graphs can appear deceptive; remembering that the lines do not represent vortex width which was discussed in more detail in the previous chapter. Additionally, these graphs also emphasize the offset pressure tap configuration on either wing in relation to the vortex paths.

The wing remains reasonably stable for \(\alpha < 10^\circ\) and the results produced from the vortex maps correlate quite accurately with static experiments conducted by Verhaagen et al. detailed in Fig.23a. The only exception discovered between these results was for the main wing vortices at \(\alpha = 5^\circ\). Verhaagen\textsuperscript{1} observed that the main wing vortices extended well beyond the trailing edge with no breakdown evident over the wing. Experiments conducted in this research project found that breakdown appeared to occur at approximately \(x/c = 0.75\).

Whilst the root cause behind the formation of roll attractors is still largely unknown, the flow field passing over the slumped starboard wing gradually diminishes with an increase in AoA. This leaves the starboard vortices with weaker vortex cores that also significantly alter vortex behaviour. The weaker influence of the vortices on the starboard wing creates a condition where the vortices begin to move inboard towards the centre line of the wing. Without the presence of the roll attractor, research discovered that these vortices behave differently as can be seen in sketches detailed in Fig.23.

The influence of the roll attractor reaches its maximum amplitude of \(\phi \approx 44^\circ\) at \(\alpha = 25^\circ\) and begins to decay until the wings return back to level at \(\alpha = 33^\circ\). Fig.23c highlights the return of a symmetric flow field over the wing with the vortices now acting back on predicted paths. Therefore the region for assessing valid results was found to be at angles less than \(\alpha = 10^\circ\) and extending beyond \(\alpha = 33^\circ\). This region basically removes an area of the test envelope where the roll attractors corrupt the results. This does not present any major limitations as the strongest region of wing rock exists at angles of attack \(\alpha > 37^\circ\).

C Analysis of Valid Pressure Measurements

The graphs shown in Fig.24 represent a comparison of unsteady surface pressure measurements at \(x/c = 0.6\) for the port and starboard wing. The pressures readings were transformed using equation(1) to non dimensional pressure coefficients which represent multiples of the dynamic pressure.

\[
C_p = \frac{p - p_\infty}{q_\infty}
\]  

(1)

For \(\alpha = 0^\circ\) shown in Fig.24a, pressure measurements located at the same position on either wing reflected that the pressures and flow behaviour were similar. The similarity of these measurements indicate the expected result for a wings level orientation.

At \(\alpha = 10^\circ\), the starboard wing has lowered to an average roll angle of \(\phi \approx 28^\circ\). Fig.24b shows that for this roll angle, the port wing is experiencing much lower pressures than that of the starboard side. Lower pressure coefficients represent the presence of greater vortical lift acting over the wing. The roll orientation of the much higher port wing reflected these lower pressure values in the results. Likewise the starboard wing was observed during flow visualisation to have weak vortices that reflect a higher pressure co-efficient on this side of the wing.

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Figure 23: Static and dynamic vortex trajectories, (a) Static $\alpha = 5^\circ, 10^\circ, 15^\circ, 20^\circ$, (b) Dynamic $\alpha = 5^\circ, 10^\circ, 15^\circ$, (c) Dynamic $\alpha = 23^\circ, 28^\circ, 33^\circ$.

When the wing passes through $\alpha = 27^\circ$, an even greater spread of pressure between either side of the wing has now developed. The average roll angle has further increased to $\phi = 42^\circ$; indicating the vortical lift has increased even further on the port wing as illustrated in Fig.24c. An assessment of these results have shown that the pressure acquisition system is successfully capturing pressure imbalances over the wing.

Fig.25a represents a region where strong wing rock is experienced right up to the end of the test envelope ($\alpha = 42^\circ$). In this region, the roll attractor maintains an equilibrium point around $\phi = 0^\circ$. The trend clearly indicates in this graph that pressure fluctuations are oscillating in opposing harmony with each other as one wing rises whilst the other lowers. Nelson and Pelletierconcluded that a destabilising moment appears necessary as a mechanism to sustain wing rock created from flow field time lags relating to vortex induced lift. This phenomena accounts for the presence of hysteresis in the system.

When a delta planform enters oscillatory motion, the vortex parameters will be out of phase with the roll angle$^{23}$. Fig.25a supports this analysis showing that there is a distinct phase shift between the pressure and roll measurements taken over the wing. The phase shift develops from time lag effects resulting from the static and dynamic vortex positions mentioned earlier in Fig.4. The time lag effects resulting from this out of phase relationship are highly dependant on the frequency and amplitude of the oscillatory motion$^{23}$. This analysis clearly supports the success of the pressure acquisition system to capture dynamic motion.

**D RASB Results**

Fig.25b displays the results of pressure measurements during the application of RASB. The fundamentals behind the RASB technique as discussed earlier in this document, were not the focal point of this project. However it was considered beneficial to test the ability of the pressure acquisition system to interpret these results to aid in development of future rule base commands into the controller.

Testing was conducted by directing compressed air to the RASB ports at 60 psi to the starboard main...
Figure 24: Comparison of port and starboard pressure tap locations (a) $\alpha = 0^\circ$, (b) $\alpha = 15^\circ$, (c) $\alpha = 27^\circ$.

and strake air chambers. The pictures shown in Fig.26 display the alteration of the flow field with the application of RASB. The results shown in Fig.25b clearly highlight that with the application of RASB, the main vortex on the starboard wing significantly decreased in pressure. At the same time there was a sharp rise to the starboard wing which reflects that RASB contributed to vortical lift and was not a reaction force in response to the delivery of compresses air. When the RASB air ceased to be delivered, the wing returned back to its pre RASB condition.

E Summary

Despite the limitations of valid data over the entire test envelope, there were several areas of the flow field that were assessed as suitable to test the performance of the pressure acquisition system.

The system successfully demonstrated the ability to capture both dynamic and static results over a range of different test parameters. It also demonstrated the achievement of meeting the project goals; especially the capture of data associated with the phase lag effects experienced during wing rock motion. The variety of successful parameters tested during these experiments will provide additional information to the controller in support of developing ruled based commands in the future. It will also aide in providing real time data that will ensure solid performance of the controller due to the ability to add additional information in the form of feedback response signals.

VIII Conclusion and Recommendations

A Conclusion

Past research has shown the capability of using a flow management technique coupled to a suitable controller to suppress the motion of wing rock on single delta wings. The motion on double delta planforms however
Figure 25: Surface pressure measurements (a) Wing rock phase relationship $\alpha = 37^\circ$, (b) RASB applied $\alpha = 5^\circ$.

is more complex. The aims of this project were to gain a better understanding of the flow field interacting with these planforms. To achieve this result, the project was broken up into discrete phases that involved dynamic surface pressure measurements, free-to-roll responses, and flow visualisation.

To the author’s knowledge, dynamic surface pressure measurements on a double delta wing undergoing wing rock motion has never been attempted. Before any experiments could be conducted to meet this goal, the design of a pressure acquisition system and a new model that accommodated pressure taps had to be designed and manufactured.

Testing revealed the complications associated with the flow field acting over the surface of double delta wings. The flow field becomes complex due to the axisymmetric force and moment imbalances arising from the interaction of strake and main vortices on either side of the wing. The phenomena associated with vortex lift off and vortex breakdown have been widely published as some of the major contributors to these complex interactions. However the influence of roll attractors in this project was noted for its problematic characteristics. Whilst other research bodies have also observed non centred roll attractors, it was surprising to learn that the effects from this behaviour leading towards vortex displacement have never been published. Even more puzzling was the underlying fundamentals that created a positive roll moment as the angle of attack was increased. It is quite possible this condition could arise from local effects that are set in motion from the ACME wind tunnel or test equipment. It is difficult to conclude a final result in the absence of detailed research conducted at other institutions to compare the results.

Flow visualisation proved an invaluable tool to validate the results. The laser sheet method was a very effective tool however it revealed a limitation when it came to capturing video footage of the wing in motion. The human eye is much more sensitive to viewing laser illumination in low ambient light. Cameras stumble to achieve quality in this environment due to the limitations imposed on the aperture and fast shutter speeds. Attempts to analyse the flow with a high speed scientific camera for these reasons proved ineffective.

Without the use of this flow visualisation technique, it would have been impossible to interpret the results. The laser sheet method was a very effective tool however it revealed a limitation when it came to capturing video footage of the wing in motion. The human eye is much more sensitive to viewing laser illumination in low ambient light. Cameras stumble to achieve quality in this environment due to the limitations imposed on the aperture and fast shutter speeds. Attempts to analyse the flow with a high speed scientific camera for these reasons proved ineffective.

During angles of attack where the secondary vortex was not evident, the strake vortices were witnessed to extract flow energy from the main vortices causing them to experience premature vortex breakdown. When the secondary vortex was present, the main wing became more dominant by extracting additional flow from both the strake and secondary vortices. This was the only period throughout testing ($\alpha = 23 - 33^\circ$) where the strake vortex weakened before the main vortices and began to breakdown. It is interesting to note that the secondary vortex becomes evident as the wing reaches its maximum average roll angle of $\phi \approx 44^\circ$. From $\alpha = 25^\circ$, the roll angle (formed from the roll attractor) begins to deteriorate until the wing return back to $\phi = 0^\circ$ at $\alpha = 33^\circ$. It may well be that the secondary vortex begins to alter the flow field condition that creates a deterioration of the roll angle until it is seen to disappear at the same time the planform
returns to a wings level orientation.

The pressure acquisition system proved very successful in achieving the project’s aims despite the difficulties experienced from vortex displacement. A series of test parameters revealed that this system was capable of measuring predicted results. The data was also shown to correlate to other experiments conducted in this field which provides further assurance that it is capable of achieving the results. To further elevate this research, investigations into re-orientating the pressure taps to cope with vortex displacement would provide tangible results in expanding the measurements achieved from the entire test envelope.

The research conducted in this project adds another module to the work already developed by Ong, Wong, Campbell, and England. Future research of designing a more robust controller and integrating these components into it, should provide an extensive leap forward into developing a control system to suppress wing rock.

B Recommendations

Several recommendations were incorporated into this project from suggestions provided by Campbell and England discovered during their research. Not all of these recommendations strived towards improving experimental results. England suggested that the models designed for future work which are primary milled from aluminium should contain a steel lower plate to improve the wing rock characteristics. The reasoning behind this was that Campbell’s model which was mainly aluminium with a steel plate, demonstrated solid wing rock characteristics. England’s model was made entirely from aluminium and had poor wing rock characteristics. Therefore during the design of a new model for this project, the opportunity was taken to test lower cover plates made from different materials. During the design of the new model, various metals were also modelled in Catia to determine the centroids in order to find a selection that ensured that model was balanced at its geometric centre. A steel plate was identified as the most suitable substitution to meet this requirement. Actual testing revealed that the aluminium plate promoted the best wing rock...
characteristics for the new model. The point being made here is that a steel plate does not guarantee better characteristics.

Additional weight added to the lower surface of England’s model did eventually provide enhanced wing rock characteristics whilst on the new model it reduced the performance. The underlying problem was that England chose to decrease the voids of the air chambers to increase RASB response times. This meant that more material was distributed towards the wing tips which significantly increased the model’s mass moment of inertia. This was the likely reason behind poor wing rock performance.

Campbell’s model on the other hand, had much greater voids within the wing to accommodate the air chambers. This ensured that the wing had a lower mass moment of inertia and good wing rock characteristics. The model designed in this project also opted for large internal air chambers to ensure the model had a low mass moment of inertia. This will ultimately have the follow on effect of time lags when the RASB is utilised in future research. In order to overcome this problem, the design provision of a removable cover plate would allow for a lighter material to fill the voids and reduce the internal volume of the air chambers.

Another design issue that was incorporated into the new model was to strengthen the attachment of the lower cover plate through the use of screws. This design handled pressures in excess of the recommendations proposed by England of 60 psi. However the tubing that ports air into this area of the wing is fragile and would depart from the attachment at the rear of the model due to the build up of a large back pressure. Likewise the interconnecting tubing that reduces the model’s plumbing to accommodate miniature piping was found to also blow apart. Therefore the tubing utilised in future research should be completely overhauled to handle these much larger operating pressures.

The largest design issue that flawed the performance of the new model was the pressure tap configuration over the wing. It would be extremely difficult to provide an arrangement that covered all predicted vortex paths over the test envelope. Therefore a solution to this problem would be to arrange the pressure taps over the surface of the wing in a more traditional style. This would involve several spanwise rows at selected chordwise positions on the model. It would be advisable to avoid having the configuration on one side of the wing only, as the formation of the roll attractor sets in motion different characteristics over either side of the wing.

The reconfiguration of the pressure taps to meet this requirement wouldn’t require a complete redesign of a new model. The current plumbing could be removed and the holes over the surface of the wing could be filled with a metal putty such as Devcon. This filler would be capable of holding the structural integrity of the air chamber when pressurised.

Another recommendation that could be incorporated into future research is to paint the wooden parts of the wind tunnel test section with matt black paint. The improvements incorporated into the wind tunnel by providing a glass wall significantly enhanced the flow visualisation results. However, this resulted in additional scattering of laser light within the test section where the model is mounted. The reflected light did not severely impede the visualised results, however the reduction of any scattered light would offer improved results. After an exhaustive consultation process with several staff members, no objections were raised as to why this improvement could not proceed.

C Further Research

Further research into the formation of the roll attractors is crucial. This factor alone will hinder the progress of maintaining a wings level attitude by the wing rock controller. One of the more challenging areas to control this behaviour will be in the minor wing rock region where the wing oscillates around a roll attractor. Whilst these characteristics have also been witnessed by other research bodies, it is difficult to correlate the results of vortex displacement to isolate if the cause is a true aerodynamic characteristic or the influence of local test equipment.

Conducting further analysis of vortex displacement will also provide tangible benefits in resolving a new pressure tap configuration. This analysis may lead to the requirement of expanding the amount of pressure taps over the surface of the wing in order to gain a larger footprint. This will also involve further investigations into equipment capable of handling more channels. Scannivalve configurations require a settling time for each pressure reading and hence would not be suitable for a dynamic situation.

Deeper analysis of this requirement may also reveal that it is not necessary to know the conditions of the entire flow field. Control inputs provided from a smaller number of pressure taps mounted in critical areas on the wing could also serve to provide enough information to the controller. The data displayed in Fig.25a showed that the pressure acquisition system was quite capable of determining dynamic motion by comparing just two pressure taps on either side of the wing. Fewer pressure tap requirements would also be beneficial in reducing the roll resistance from additional plumbing attached to the wing.

On the other hand a much larger footprint covered by additional pressure taps would allow for the precise mapping of the vortex paths to gain a better understanding of the flow field characteristics that lead to the
formation of roll attractors, vortex displacement, and vortex breakdown locations.

Computational modelling may also present another perspective in the analysis of the dynamic flow field over the wing. This form of analysis has been used quite extensively for single delta wings to provide a deeper level of analysis. Computational modelling offers the ability to slow down the flow field by allowing the model to advance through small time steps. This is a significant advantage as high speed camera footage during experimental testing is limited due to the requirement of high shutter speeds and low ambient light conditions.

With the availability of both single and double delta wing data from previous experiments within ACME, a simple single delta model could be developed initially to compare against experimental results. If this proves successful, the model can become more intricate in detail and progress towards the complicated flow field experienced on double delta wings. These results may unlock some of the mysteries surrounding the behaviour and formation of the roll attractor. It may also provide answers to whether the wind tunnel or test equipment plays a role in disturbing the flow field.

One final note about the out of phase relationship between the roll and pressure data. Data feeds from the potentiometer and pressure acquisition system are capable of providing information about the phase lag to the wing rock controller. Once this lag is known, the controller can be programmed to become more intelligent. The aim here would be to apply the flow management technique before the wing reaches a predetermined roll angle so that the applicable vortices could be manipulated before uncharacteristic behaviour develops. In this manner wing rock suppression would be pre-emptive rather than reactive which is the method this motion has been controlled by in projects to date.

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**Appendices**

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