Analysis of an in-flight water refilling system for single-engine fire bombing aircraft

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This thesis will analyse the viability and safety of an in-flight water refilling system which was originally designed and tested by an Australian in 2007. The design in question consisted of a ski/scoop mechanism which was attached to the aircrafts fixed undercarriage. Currently the only system that exists worldwide for filling such an aircraft is the modification and addition of after-market floats. These cost in excess of $1M and significantly reduce the aircrafts' useful payload, range and manoeuvrability which have the overall effect of reducing both the capability and performance. Designing a more efficient, cheaper system has vast potential particularly in fire-prone countries. In order to assess the safety and viability of this design, extensive theoretical calculations have been compared to real-world experimental data in order to come to an accurate result of the forces and moments acting on this aircraft during the refilling process. These have then been compared with data calculated from a control surface analysis, in order to determine the aircrafts controllability in this flight condition. The final outcome is that this system, although theoretically possible in the sense of aircraft controllability under certain conditions, is not safe for the intended purpose on aircraft.

Contents

I. Introduction

A. Historical Background

Every year worldwide, out of control fires are responsible for hundreds of deaths, widespread loss of infrastructure and the devastation of millions of square kilometres of forest and bushland. Thousands of fixed-wing aircraft, many specifically built for fire bombing and some modified for the purpose, are utilised in order to fight fires across the globe. One aircraft which is used prolifically in this role is the Air Tractor AT-802, an aircraft which was originally built as a crop dusting aircraft. This aircraft, classed as a 'Single Engine Air Tanker' (SEAT), has become popular due to its excellent low level handling properties, large internal payload and low operating costs (Carlton and Dudley, 1999). However this aircraft, and others like it, have one major flaw; they cannot refill their water supply whilst airborne. What this essentially means is that after dropping its payload on a fire, the aircraft must return to an airfield, land, reload, takeoff and return to the fire.

In 2007 an Australian pilot by the name of Colin Pay began pioneering a revolutionary water scoop system attached to the aircrafts' fixed undercarriage, which would allow the AT-802 he was flying to refill its tanks from the surface of a large body of water. The scoop was part of a larger ski mechanism, which was lowered in flight and allowed the aircraft to skim across the surface and refill its internal tank. Tragically, on one of his test runs the aircraft over-rotated, struck the surface of the lake and rapidly sank, causing Mr Pay to lose consciousness and drown (ATSB, 2009).

B. Motivation

This system was the first of its kind to be designed and tested, having the potential to revolutionise the firebombing aircraft industry. Unfortunately during the development of Colin Pay's ski, there was little detailed analysis of the design and no scaled testing of the device prior to full scale prototype flight testing. This thesis aims to fill the research gaps, assess the viability of a system such as this and further optimise this method such that further testing may be able to be carried out in the future.

C. Aims

A list of project specific deliverables includes:

1. A detailed design report on the conceptual design and testing of the model.
2. A series of sketches of the proposed scale model, including a comprehensive theoretical analysis.
3. A working scale model of a ski/scoop system for a single-engine fire bombing aircraft.
4. A summary regarding whether this is a viable system, especially in regards to safety and aircraft dynamics.
5. Observations and recommendations on this type of design compared with other possible designs.

II. Historical Theories and Calculations

A. Planing Theory for Flat Rectangular Sections

Hydrodynamic planing refers to when an object is moving over the surface of a fluid at a speed such that the majority of the reactive force is due to hydrodynamic lift, as opposed to the objects buoyancy (Shuford, 1954). During the 1940s and 50s, much research was put into the study of hydrodynamic planing, an area which is still often poorly understood today. Hydrodynamic planing is difficult to analyse due to the 3-dimensional effects that occur. Similar to an airfoil on an aircraft, the pressure difference between the top and bottom surfaces cause a significant amount of 'cross flow' which creates the equivalent of induced drag as vortices are shed off the sides (Shuford, 1957). Coupled with this are the wake effects, which have been found to change with respect to Froude number. These are often almost impossible to analyse without the use of pre-existing data.

For the situation with the ski, a number of important factors exist that need to be considered when performing any kind of analysis. Firstly, any force due to buoyancy will be ignored. While this may be trivial in terms of the ski whilst at rest, when in motion and the flow at the back of the ski is in the planing condition, a small buoyant force will be present. This force is due to the air cavity that effectively forms on the upper surface of the ski, with the difference between the atmospheric and hydrostatic pressures resulting in a small net force upwards. However since the angle of attack will only vary between approximately 0 and 10°, this force will proportionally be very small and thus can be neglected.

Presented below are a number of equations which have been derived from a number of different researchers. There is still no definitive theoretical analysis that matches perfectly to experimental results, however by plotting the curves for every equation it can be verified how accurate the testing is. The various researchers conducted a number of experiments and then found equations to match the curves produced by their experimental findings.

Perring and Johnston (1935) $C_L = 0.90 \times AR^{0.42} \times \alpha$

Perelmuter (1938) $C_L = \frac{2 \times AR \times \alpha}{1 + AR}$

Sorttof (1944) $C_L = 0.85 \times AR^{0.5} \times \alpha$

Sedov (1947) $C_L = \frac{0.7 \times \pi \times AR \times \alpha}{AR + 1.4}$

Siler (1949) $C_L = \frac{\pi \times AR \times \sin(\alpha) \times \cos(\alpha)}{AR + 4} + 0.88 \times \sin(\alpha)^2 \times \cos(\alpha)$

Korvin-Kroukovsky, Savitsky and Lehman (1949) $C_L = 0.012 \times AR^{0.5} \times (57.3 \times \alpha)^{1.1}$

Shuford (1954) $C_L = \frac{0.5 \times \pi \times AR \times \alpha}{1 + AR} \times (1 - \sin(\alpha)^2) + \sin(\alpha)^2 \times \cos(\alpha)$

Perring and Johnston, Sottorf, Sedov and Korin-Kroukovsky, Savitsky and Lehman all used the method of fitting an equation to experimental results. They conducted numerous experiments using flat plates in the planing condition and gathered the resultant data from the lift force being produced. For this reason, the equations produced by these researchers have specific constants in them which can only be derived from experimental results. Perelmuter and Shuford attempted to solve the problem purely analytically and thus produced equations which were free of the specific constants which are present in all other theories. These calculations were based on thin-airfoil lift line theory, however Shuford (1954) in particular made an effort to subtract the 'suction' component of thin airfoil lift from the upper surface of the flat plate, as well as account for the 'cross flow' on the lower surface of the plate. Thus, it can be assumed that Shuford's formula is arguably the most accurate; however the other theories are still relevant due to their close association with experimental results. For the reason of comparison, Siler's formula will also be utilised in order to compare against experimental results collated during testing. The reason for this is that Siler took Perelmuter's theory and modified it, by fitting the curve to experimental results he obtained from his own comprehensive testing program (Siler, 1949).

B. Drag

In a later paper, Shuford focuses more on the concept of drag in the pure planing condition. He again collates and analyses a number of previously written papers, before conducting a number of experiments. He found that the two main components of drag are skin friction and induced drag. Although during earlier research for this thesis it was thought that classic pressure drag was a major factor, Shuford's (1957) paper makes it clear that this is not the case. This is primarily due to the free surface of the double-fluid control volume, as the pressure differences on either side of the ski do not cause pressure drag as previously thought. As experimental results showed, the total drag was simply a function of the skin friction and cross-flow effects. The cross-flow is defined as the component of the fluid velocity on the underside of the ski that is travelling perpendicular to the freestream flow path. Much the same as classic induced drag on an aircraft wing, the induced drag on the ski is caused by the pressure difference between the top and bottom surfaces, which causes flow to create a vortex railing off the ski edge. Due to the much higher density and viscosity in water as opposed to air, the induced drag on the ski is far greater than the equivalent scenario in air. These vortices, being continually shed from the ski whilst in motion, travel backwards and are largely responsible for the formation of the visible wake. This wake often rises up above the surface of the water, due to the positive pressure head imparted on this localized volume of fluid. Unlike an aircraft wing, the strength of the vortices increases with velocity provided the AoA is held constant, thus meaning that drag increases proportionally (Shuford, 1957).

In his paper Shuford (1957) proposes the induced drag could be found using the following formula.

$$C_{D.i} = C_L \times \tan(\alpha)$$

This can be validated using trigonometry as Figure 1 in Appendix B explains, since the normal force component can be broken down into lift force and drag force which act perpendicular and parallel to the freesteam direction respectively.

The skin friction component is simple to calculate and has been found using well known theories. First the Reynolds number was calculated for the range of speeds the model and full scale skis will be operating in. As shown in Figure 4 in Appendix B, every single point lies well above the laminar-turbulent transition region, meaning the flow can be assumed to be completely turbulent for both scenarios over all flow speeds. Thus, the following formula can be used to calculate the ski friction drag for both the model and full scale case (Munson et al, 2010):

$$C_{D,sf} = \frac{1.3282}{\sqrt{Re}}$$

Figure 5 in Appendix B plots the skin friction drag of the model ski.

Finally, the overall drag coefficient is simply $C_D = C_{D.sf} + C_{D.i}$ (Shuford, 1957)
Because the induced drag is dependent on the AoA and skin friction drag is dependent on velocity, the overall drag coefficient will be specific to a defined AoA setting at a defined speed.

The maximum skin friction drag coefficient is 0.002845 which occurs at low speeds, however due to the exponentially decreasing relationship it appears to asymptote at approximately 0.0007. When the information for the full scale ski in a flight condition of 90 knots is applied, a skin friction drag coefficient of 0.000299 is found. Due to the relationship that exists, at such high Reynold's numbers the gradient of the line will be approximately zero. Thus, it can be assumed that the skin friction drag coefficient is 0.000299 for the full scale ski in all flight conditions.

The cross-flow effects correlate to the exact same principle as induced drag on an aeroplane wing. The transverse flow develops due to the significant pressure difference between the lower and upper surface of the ski. This causes some of the flow to travel perpendicular to the freestream directly until it reaches the ski edges, at which point it travels around and creates a vortex.

III. Aircraft Controllability Analysis

A. Positive Aircraft Control

In order to assess the safety and viability of this system, it is important to calculate the maximum magnitude of both elevator and rudder force that the aircraft can apply. If the ski forces exceed these values, it can be assumed that the aircraft is uncontrollable. For the purposes of this analysis, uncontrollable is defined as when the moment due to drag on the ski equals the moment due to the corresponding tail surface at maximum deflection from the neutral position.

Due to the nature of the aircraft control surfaces, namely that they are unslotted and simply rotate up or down from their original position, they can be modelled as plain flaps. Plain flaps, when utilised on a wing, will create a great lifting force due to the increase in both camber and angle of attack of the wing. This lift force can be applied to the control surfaces in order to determine the maximum control authority that these surfaces can provide (Raymer, 2012).

Assumptions:

a. While in contact with the water surface, the aircraft maintains in steady level flight
b. The horizontal tail surface has no angle of incidence on the fuselage
c. The aircraft does not experience a change in pitch or yaw attitude
d. Elevator and rudder can be modelled as a plain flap
e. End sections of elevator and the tip of the rudder can be modelled as flat plates (since they're well beyond the stall condition at maximum deflection)
f. Any effects due to the rotating air from the propeller is neglected
g. Lift forces from tail surfaces can be non-dimensionalised for comparison

From the aircraft specifications found in FAR 23, the maximum positive elevator deflection was found to be 29° and the maximum rudder deflection is ±24°.

Because the lift coefficient is a function of control surface deflection there will be a linear relationship between these two variables. When a control surface is deflected, the time between deflection and lift onset is not instantaneous. This is due to a number of reasons, however primarily because the flow needs to reach steady conditions once again after a disturbance. What this essentially means is regardless how fast the control surface is deflected, there will still be a small ‘lag time’ during which the full lift force will reach its maximum. When coupled with pilot reaction times, the time between the pilot realising a control input is needed and the respective control surface actually achieving steady flow can be a significant variable when analysing the safety of the system (Anderson, 2011).

B. Pitch Controllability

Using the formula located in Appendix C, the lift coefficient for the horizontal tail at maximum deflection was found to be 1.9287. This corresponds to a moment coefficient of 11.0512. For the aircraft to maintain equilibrium, the moment coefficient from the ski system cannot exceed the moment coefficient for the horizontal tail. By factoring in the moment arm for the ski system, the maximum allowable drag coefficient for the ski system 5.0780. Since there are two skis, this corresponds to a drag coefficient of 2.5390 per ski. If the aircraft is travelling across 20°C water at 90 knots, the total lift force produced by the horizontal tail at maximum elevator deflection is 6,072 N. By completing a moment calculation, the maximum allowable ski drag force in this condition will be 15,986 N, which equates to 7,993 N per ski.

C. Yaw Controllability

The lift coefficient for the vertical tail was calculated using the same process as outlined above and in Appendix C. For this case, the lift coefficient was found to be 0.6209, which corresponds to a moment arm of 3.8762. Therefore, the maximum allowable drag coefficient after factoring in the moment arm is 2.7073. It is important to note that this analysis is just for a single ski, as the drag of the two skis together will cancel each other out. Although the system is designed to have both skis in equal contact with the water surface, this analysis is still extremely important as the crash that killed Mr Colin Pay was attributed to a loss of control in the yaw axis.

As can be deduced from the above calculations, the maximum allowable drag is higher for yaw controllability, meaning that the pitch stability is the more critical stability as the maximum allowable drag force is lower. Once again in a flight condition of 90 knots, the maximum horizontal lift force produced by the vertical stabiliser at full rudder deflection is 2,527 N. This equates to a maximum allowable ski drag force of 11,018 N.

IV. Further Analysis, Evaluation and Testing

A. Finite Control Volume Analysis

Prior to analysing the system in order to gain a theoretical understanding of what the forces will be, a suitable control volume needs to be drawn. This will allow justifications to be made which will simplify the problem. Drawing the control volume for this system is not straightforward. While it can simply be modelled as a water-jet momentum deflection from a flat plate, this would not be accurate due to the two-fluid interface over which this ski will operate. Figure 1 in Appendix B displays the control volume used for the analysis of the ski. As the fluid enters at freestream velocity from the left, it can be assumed that it impinges on the ski surface and changes its direction, such that it travels parallel to the ski. Therefore, the ski can be modelled as a streamline through which no mass can travel. The lower streamline, which runs parallel to the water surface, can also be modelled as a streamline for the purposes of this analysis. However this streamline is assumed to be at a distance far enough away from the ski such that it feels no influence from the ski deflecting the flow above this. Thus, it is assumed that no mass crosses this. The inflow line, on the left side, indicates where the freestream flow enters the control volume. On this line, flow is assumed to travel perpendicular and all from left to right at constant velocity.

B. Non-dimensional Results

For the purposes of accuracy, results obtained in both theoretical and experimental methods have been non-dimensionalised in this paper. This process effectively cancels out the variables such as density; velocity etc such that results obtained in different conditions should produce the same non-dimensional result.
In terms of application within this thesis, non-dimensional results will allow a direct

C. Similarity

In order for the testing to be both meaningful and accurate, a high degree of similarity must be achieved between testing conditions and theoretical flight conditions of the full scale ski on the aircraft (Munson et al, 2010).

Dimensional similarity: The model ski is exactly a 50% scale model of the full size ski. The full scale ski's dimensions are a full length of 1m, a wetted length of 0.85m and a beam of 0.3m. This results in an area of 0.255m^2 and an aspect ratio of 0.3529 (it's important to note that the wetted length is being used in these calculations, as opposed to the true length). The scale model ski, whilst having an area of 0.06375m^2 still maintains the same aspect ratio of 0.3529. This means that dimensionally, the model and the full scale ski are similar.

Dynamic similarity: While many fluid-based experiments require the matching of the Reynolds number, this experiment requires matching of the Froude number due to the two-medium interface that the ski lies on. The Froude number is defined as: $Fr = \frac{V}{\sqrt{g \times l}}$ (Munson et al, 2010)

For the case of the full scale ski which has a wetted length of 0.85m and will travel at a velocity of approximately 90 knots, the corresponding Froude number is 31.2. In the case of the test ski however, which has a wetted length of 0.425m and a maximum test speed of 15 knots, the Froude number is equal to 7.35. Although this is a closer match than a comparison of the Reynolds numbers, which have values of 3,270,157 and 76,280,120 for the test ski and full scale ski respectively, the inability to match the Froude number will contribute significantly to the errors within this analysis. Unfortunately given the test conditions, for the Froude number to match the wetted length of the test ski would need to be 0.023m, which is completely unrealistic to achieve. The resultant difference in Froude number will cause a certain degree of error in the numerical results, however these can be accounted for and any trends found during testing should be applicable to the full scale design.

D. Testing

The testing process consisted of 5 test sessions, each lasting on average between 2-3 hours. During this cumulative 10-15 hours of testing, the ski was able to be tested at different angles of attack, different speeds and different surface conditions. Surface conditions were completely weather dependant, however they range between completely calm to conditions with surface waves up to 20cm high. In the latter conditions it became extremely difficult to measure data accurately; however it proved to give excellent qualitative results as to how the surface conditions affected how the ski behaved. Tests were conducted by holding a constant angle of attack and changing the speed of the boat. This had the effect of eliminating variables and thus also eliminating the uncertainty of the experiment.

The temperature of the water was estimated to be approximately 20°C; therefore this temperature was used in the theoretical calculations as it was also deemed as being similar to the conditions the full scale ski would likely encounter. Due to the extremely low dependence in the water properties of density and viscosity in the calculations themselves, it was assumed that a change in water temperature would contribute very little to an error between theoretical and experimental results.

E. Calibration

In order to ensure that the test results were as accurate as possible, it was a requirement to calibrate PLTOFF Sarah Budd's surface force measurement device, which was used for the testing. To do this tests had to be carried out which could be compared to well known and easily calculated data. It was decided to calibrate the device with a spherical ball of approximately 25cm diameter which was set to be approximately 30cm under the water surface.

F. Error analysis

The uncertainly or error of the experiments were calculated using a standard error analysis by means of the formula below (Taylor, 1997).

$$\%\,error = \left(\frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c}\right) \times 100\%$$

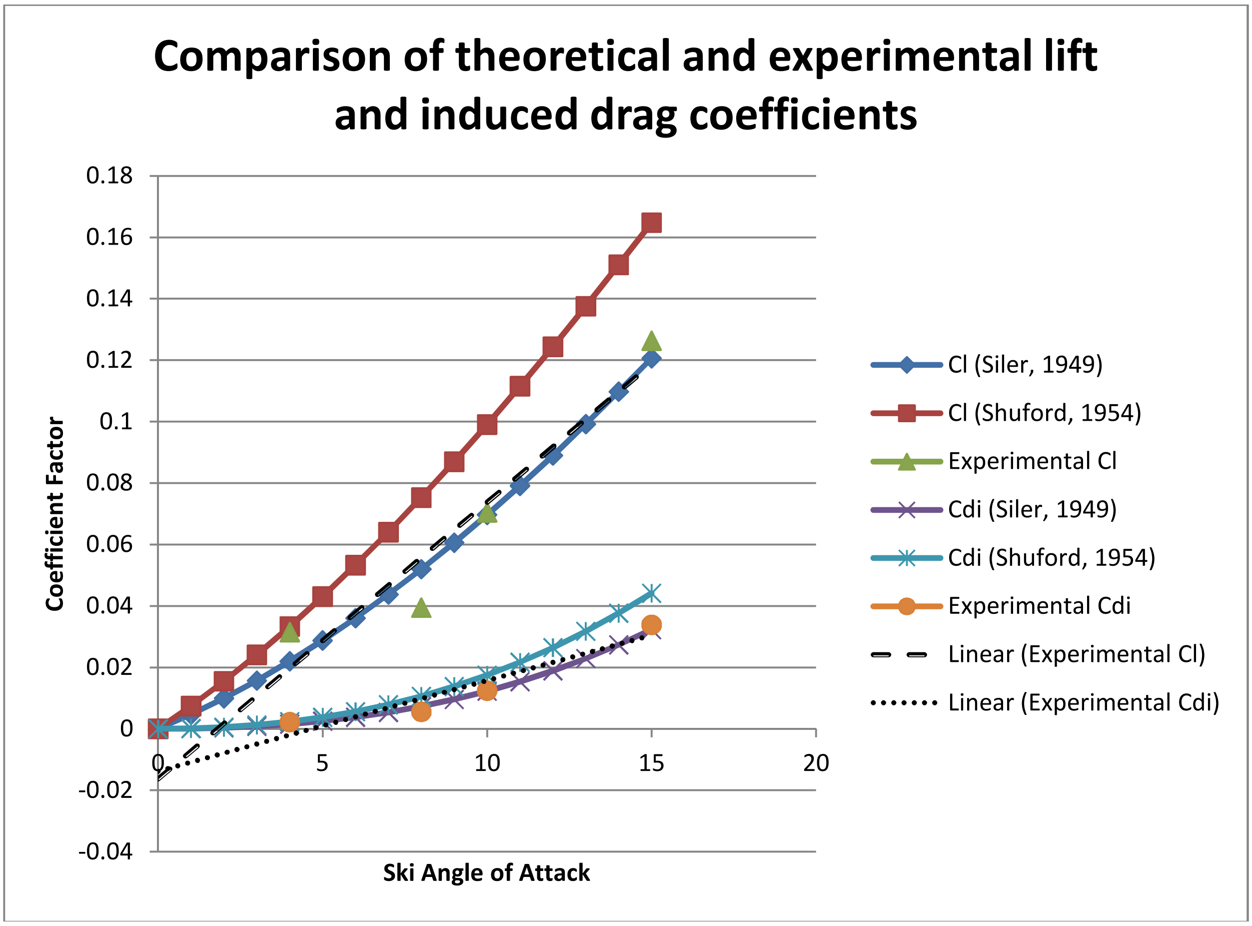
In this case, the variables a, b and c represent the measured strain, angle of attack and boat velocity respectively. The Vishay strain indicator measures in increments of 0.01 kg, which therefore means the uncertainty of this measurement is ±0.005 kg. The angle of attack setting was slightly more problematic. The increments used on the angle indicator, the device used to measure the angle of attack, was 1°. Using the same method as previously, this means the theoretical uncertainty of this measurement is 0.5°. In reality however, the actual error will be higher due to the shear difficulty in maintaining a constant angle during the testing, especially in the face of high drag bow wave interactions which cause a large pitch down moment. Using footage from the

testing, it can be reasonably accurately estimated that the error in measurements is approximately ±1°, an additional ±0.5° higher than the theoretical value.
Finally, the error for velocity was estimated to be ±0.2 knots. Similar to the AoA, the measurement increments for velocity were 0.1 knots which resulted in an uncertainty of ±0.05 knots; however the true error was estimated to be ±0.2 knots simply due to the difficulty in maintaining a steady, constant speed in the boat. The velocity readings were read using two separate Garmin GPS units and thus can be assumed to be accurate themselves.

V. Results - Quantitative and Qualitative

For the case of the ski, it is clear to see during testing when planing begins to take effect. While quantitatively there is an increased in the measured force, qualitatively it is clear to see that the region of reverse flow across the rear end of the ski moves backwards, to the point where the fluid at the rear of the ski travels straight backwards and impacts into the wake.

The graph below shows the experimental data plotted against the data from the two previously chosen papers, being Siler's and Shuford's. Despite it being slightly lower than both historical plots, it is clear that there is a very similar trend between experimental and theoretical calculations.



The linear equation for the lift coefficient was found to be $C_L = 0.009 \times AoA - 0.0163$, whilst the equation for the total drag coefficient was found to be $C_D = (0.003 \times AoA - 0.0138) + 0.000299$ where this is the combination of both induced and skin friction drag coefficients.

A. Bow wave interactions

Stagnation point: At various stages during testing, the model was run during periods in which the free water surface was subjected to choppy conditions. Small waves, approximately 20cm is height, were present on the surface on the water and caused significantly different results to when testing was conducted in calm conditions. For the purposes of testing, calm conditions were deemed to be when surfaces waves are approximately 5cm or less on average.

During testing in choppy conditions, it became apparent there was an interaction between the surfaces waves and the bent ski tip which caused large fluctuations in the forces which were measured. From later video analysis, the angle on the wave face and the angle of the ski tip matched reasonably closely. This, when looked at closely, caused a local stagnation point to form on the angled ski tip which hence caused a large increase in force. Due to the angle of attack of the ski and the relative angle of the ski tip, this force mainly acted in the x direction, thus causing additional drag on the ski. Due to the anchor system used to secure the testing device to the boat, it became extremely difficult to maintain a constant angle of attack on the ski testing system. Fluctuations were estimated to be approximately +/- 2 degrees. Due to the rapid increase and decrease in drag during this process, a reasonably constant 'bucking' cycle was established, where the ski essentially skipped across the water surface while producing massive changes in the overall moment.

A secondary effect of this stagnation point was to project fluid radially outwards and forwards of the ski tip. From momentum conservation, it is obvious that the force required to completely reverse the direction of the incoming fluid will be a significant factor on the overall lift and drag of the ski.

<u>Low AoA Interactions:</u> One interaction which became apparent during testing is that of the low angle of attack drag rise. From theoretical calculations it was assumed that at very low angles of attack there is a very small resultant force acting on the system; however this was proved not to be the case. At angles of attack below approximately 2 degrees the reverse flow region, also known as the bow wave or 'pile up', would spill over the ski tip and impact on the ski housing. This interaction caused a significant drag rise in the horizontal direction for the same reasons as outlined in the stagnation point analysis. In every case, the rapid drag rise would cause a moment which would in turn cause the test rig itself to pitch downwards. As the ski would begin to pitch down, the drag rise would continue to increase and thus the problem became worse. During testing, it generally required manual correction when this situation occurred as the test rig was not anchored to the boat well enough to be able to withstand the bending moment.

It was also extremely difficult to measure this drag rise. During the testing, the reactive force was causing a compressive load through the load cell which is essentially the product of the lift and drag forces acting on the ski. The load cell was only placed in the vertical direction and thus if a force was acting perfectly perpendicular to the direction of the load cell, this force would not register. As the ski pitched down, the force transitioned from a compressive load to a tensile load. What this means is that the positive lifting force reversed its direction, whilst the horizontal drag force remained in the same direction. Unlike the stagnation point interactions, the low AoA interaction produced a steady yet exponential increase in drag. As the drag increased, presumably as a function of sin(AoA), the induced moment increased proportionally and thus the pitch rate for the overall system increased with time.

<u>Aircraft Application:</u> In terms of aircraft application for the stagnation point interaction, this is likely to cause a detrimental yet not catastrophic result. The skipping effect, while drastically increasing the drag for a short period, also produced sharp local increases in the lift. On an aircraft, this is more likely to cause structural failure of the ski system as opposed to creating a moment great enough to pitch the aircraft forward to impact with the water. Due to the mass moment of inertia of the aircraft, is it not likely that the drag rise would cause a pitch down effect on the aircraft itself. However if the waves were large enough and the local drag rise produced was high enough, it may produce a short period pitch down moment that would be extremely hard for the pilot to correct for.

The other factor is that a steady state 'skipping' motion is not conducive whatsoever to water collection. Although outside the realms of this paper, from video playback of testing it became apparent that very little fluid was able to pass through the collection hole prior to the ski pitching forward and bouncing up away from the surface. The result from this is that if used on an aircraft, strict guidelines would have to be put in place such that a water collection run may only be attempted if the surface waves are below a specified height. During testing it became apparent that the model ski could safely operate at high speed in waves between 5-10cm. Any higher than this and the skipping oscillations would often occur, after which the only way to stop said oscillations would be to either slow down or lift the ski away from the water surface.

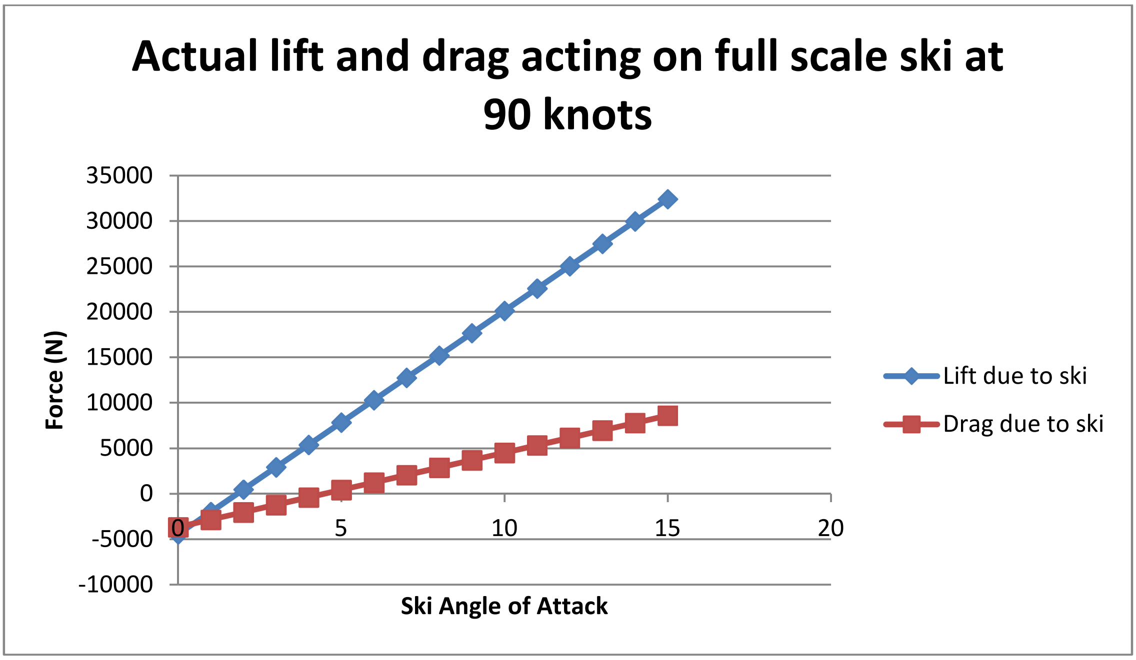
In terms of the low AoA interaction however, this has potentially catastrophic results in a full scale aircraft application. The reason for this is the exponential drag rise and the fact that a suction-like downforce is produced as opposed to a positive lifting force. The ramifications of the pilot not immediately correcting for a slight pitch down moment may result in the ski system producing a moment which far exceeds the maximum potential counter-force that is able to be produced by the horizontal tail. It is extremely possible that this low AoA interaction which a major factor in the cause of Mr Colin Pay's fatal accident. If used on an aircraft,

numerous safety systems would have to be built into the design. Such systems may include a 'breakaway' system, where the ski simply detaches from the undercarriage should a certain drag force be reached. Another potential system could be an automatic AoA-changing system, powered either by a spring or computer operated piston, where the AoA of the ski can be rapidly changed automatically should a certain moment be produced. This would at the very least prevent the exponential drag rise from occurring and give the pilot more time to correct and pitch the aircraft back up.

VI. Full Scale Application and Modelling

A. Full Scale Ski Application

Having validated the theoretical data obtained for the model ski, the same calculations can now be made for the full scale ski in order to further analyse its potential effects on controlled flight. Because of the dimensional similarity between the model and full scale ski, the full scale version will have the exact same non-dimensionalised coefficients as the model. Furthermore, because the skin friction drag coefficient was earlier found to be constant for high Reynold's numbers, this means that both the lift and total drag coefficients are simply functions of the angle of attack of the ski.



B. Controllability Assessment

To assess the controllability of this system, the full scale drag coefficients must be compared to the calculated allowable drag. Once again, the comparison will be made using a flight condition of 90 knots, for the reason that this is the speed that Mr Colin Pay was flying in the vicinity of at the time of the accident. The maximum allowable forces per ski in order to maintain both pitch and yaw control are 7,993 N and 11,018 N respectively.

Using the relationship derived from experimental results to find both lift and drag coefficients, which has been validated by historical calculations and experiments, the maximum ski AoA has been calculated. To maintain positive pitch control the ski AoA cannot exceed 14.257°, whilst to maintain positive yaw control the ski AoA cannot exceed 17.949°. This means that the critical angle for aircraft stability is 14.257° and the critical axis is the pitch axis.

At low angles, the drag rises due to both the ski tip stagnation point and low AoA interactions were difficult, if not impossible to accurately measure. However simply from qualitative results only, which itself was validated by reviewing the footage collected during the test runs, it seems that significant ski tip stagnation point interactions began affecting the ski system in waves of approximately 5cm or more. Due to the dimensional similarity, this means the full scale ski will be affected by surface waves of approximately 10cm in height or

greater. In addition to this, the low AoA interaction began occurring independent of velocity, at angles of attack of approximately 3° or less and can also be affected or changed by the height of the surface waves.

VII. Conclusion

During the design and testing of Colin Pay's revolutionary in-flight water refilling system, there was very little research and analysis between the conceptual design phase and the full scale testing phase. This thesis has not only filled that gap of understanding, but has also provided an in-depth explanation of the problems involved in this type of system. After conducting a deep level literature review and calculating a number of theoretical results based on historical calculations and experiments, the data was then compared to experimental data obtained by a 50% scale model ski.

By analysing the control aspects of the aircraft and determining what parameters must be exceeded in order to lose positive aircraft control, it has been established that this is a potentially viable system in terms of safety if:

- All assumptions made in this paper remain valid on a full scale model
- Water surface must be calm, with surface waves less than 10cm in height

Given the sensitivity of this system and in particular, the extremely fast rate in which things can change when it comes to the bow wave interactions, this system is not safe to be used in its intended capacity on aircraft. Whilst a system such as this would be a lot cheaper to manufacture and fit onto an aircraft, the restrictions in terms of the surface conditions in which this system can operate in would severely restrict its use.

The final conclusion is that this system is unsafe for the use on aircraft and the design for this particular ski system should be abandoned.

A. Recommendations

While this particular design has been proven to be unsafe for the use of collecting water, this does not detract from the fact that there is still a pressing need for such a technology to be developed. There is scope from the end of this project to investigate different shaped skis, or simply investigate an entirely new system such as a snorkel or trailing drogue etc. Given that a large factor in making the investigated system unsafe were the bow wave interactions, a study into a flared or alternatively shaped bow which may shed that bow wave would have potential. The testing method using PLTOFF Sarah Budd's force measurement device proved to be successful, so there is scope for future projects to use a similar system and testing process.

B. Acknowledgments

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