International Baccalaureate

Extended essay cover

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Candidate session number			
Candidate name			
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Examination session (May or November)	MAY	Year	2013

Diploma Programme subject in which this extended essay is registered: DESIGN TECHNOLOGY

(For an extended essay in the area of languages, state the language and whether it is group 1 or group 2.)

Title of the extended essay: HOW DOES THE DESIGN OF A WING AFFECT THE LIFT AND DRAG CHARACTERISTICS OF AN AIRCRAFT?

Candidate's declaration

This declaration must be signed by the candidate; otherwise a grade may not be issued.

The extended essay I am submitting is my own work (apart from guidance allowed by the International Baccalaureate).

I have acknowledged each use of the words, graphics or ideas of another person, whether written, oral or visual.

I am aware that the word limit for all extended essays is 4000 words and that examiners are not required to read beyond this limit.

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Please comment, as appropriate, on the candidate's performance, the context in which the candidate undertook the research for the extended essay, any difficulties encountered and how these were overcome (see page 13 of the extended essay guide). The concluding interview (viva voce) may provide useful information. These comments can help the examiner award a level for criterion K (holistic judgment). Do not comment on any adverse personal circumstances that may have affected the candidate. If the amount of time spent with the candidate was zero, you must explain this, in particular how it was then possible to authenticate the essay as the candidate's own work. You may attach an additional sheet if there is insufficient space here.

A grade EE: has much to feel proud of in this EE, and is to be commended for pursuing an EE in one of his IB higher subject areas. His obvious interest in the topic, methodical approach to exploring it, and increasingly confident understanding and application of the technical aspects of the essay can be seen throughout. used primary testing as the basis for his essay which was strongly grounded within the theoretical content of the DT IB specification. In the viva voce explained that he had found the EE process very satisfying (largely due to his interest in the topic) and enjoyed being able to choose his own topic and to actively explore it. is pleased with the finished product -- and with good reason: overall, I feel that its qualities merit it be awarded a solid A grade.

This declaration must be signed by the supervisor; otherwise a grade may not be issued.

I have read the final version of the extended essay that will be submitted to the examiner.

To the best of my knowledge, the extended essay is the authentic work of the candidate.

I spent 3 hours with the candidate discussing the progress of the extended essay.

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Assessment form (for examiner use only)

Criteria	Achievement level				
	Examiner 1	maximum	Examiner 2	maximum	Examiner 3
A research question	2	2		2	
B introduction	2	2		2	
C investigation	4	4		4	
D knowledge and understanding	4	4		4	
E reasoned argument	3	4		4	
F analysis and evaluation	3	4		4	
G use of subject language	4	4		4	
H conclusion	2	2		2	
I formal presentation	3	4		4	
J abstract	2	2		2	
K holistic judgment	3	4		4	
Total out of 36	32				

EXTENDED ESSAY – DESIGN TECHNOLOGY

How does the design of a wing affect the lift and drag characteristics of an aircraft?

Candidate Number:
Submission Date: 8 June, 2012
Supervisor:
Word Count: 3653 words

Abstract

The research question of this investigation states, **"How does the design of a wing affect the lift and drag characteristics of an aircraft?"** This question related the designs of different wings, with their aerodynamic properties, and investigated how this would affect an aircraft's performance.

This investigation focuses on three types of wings: the conventional straight wing, swept wing and delta wing. The plan for the project was to investigate the different types of drag and lift that affect these wings. This data was collected by means of making wing models and wind tunnel testing. Further research was also conducted via readings from aeronautical engineering books. In order to completely answer the research question, 2 hypotheses were created; "swept wings have a lowered drag component in comparison to conventional straight wings, allowing for greater fuel efficiency and hence are used for planes in service for longer haul flights" and "in comparison to the straight wing, delta wings will have a lower lift to drag ratio (L/D) at take-off and approach speeds".

The three aircraft that represented the wing types were the De Havilland DHC-2 Beaver; the Boeing 747-100 and the Aérospatiale-BAC's Concorde.

Results showed that the delta wing was least efficient with the lowest (L/D). Meanwhile the straight wing had a higher drag coefficient in comparison to the swept wing. To conclude, the elongation of the wing can increase the amount of drag present, whilst a slight sweep angle can reduce the drag coefficient.

Word count: 243 words

Contents

1. Introduction

As commercial flying flourishes in the 21st century, a gap in the market has caused low cost carriers such as Air Asia to open up. This increased competition means that they are struggling for survival. To aid these airlines through their difficulties, and adhere to environmentalists' concerns, reduction of aircraft's fuel consumption is of aircraft manufacturers' priority. One way to increase the efficiency of a plane is to redesign the wings.

As an IB Human Factors student, it is really interesting to see the different properties of materials and structures. This investigation would allow me to explore the connections between the theories learnt and the interesting topic of aviation. Furthermore, as an aircraft enthusiast, lift and drag characteristics of various types of wings and its effect on the aircraft's performance has always fascinated me. For instance, how the design of Aérospatiale-BAC Concorde's wings allowed her to reach supersonic speeds; and how the massive Boeing 747 even lifts off the ground, then travels for up to 15 hours non-stop at a speed of Mach 0.84, equivalent to 84% of the speed of sound were simply astonishing. The research question of,

"How does the design of the wing affect the lift and drag characteristics of an aircraft?"

was therefore developed.

From almost 5 years ago, when my passion for flying developed, it was my understanding that lift was "created" by a difference in pressure between the top and bottom surfaces of the wing. This concept was first heard about in Iron Maiden's lead singer, Bruce Dickinson's aviation program, "Flying Heavy Metal", where he described how lift was generated. (Discovery Channel, 2005) This demonstration was completed using a straight winged aircraft, and was known as Daniel Bernoulli's Principle. (MIT, 1997)

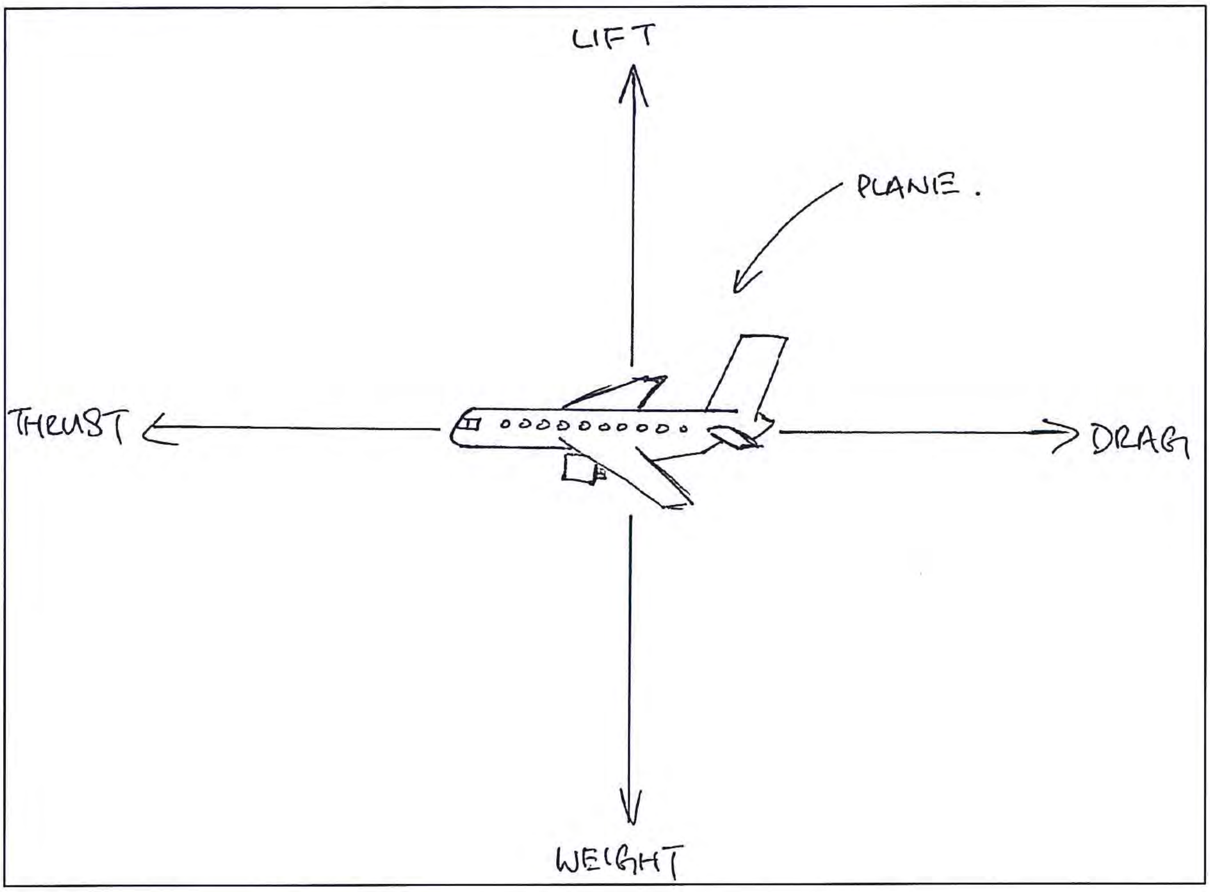
However, instead of Bernoulli's original model of a straight wing, modern jet liner manufacturers use other designs, such as the conventional swept wing, that the Boeing 747's sports; delta wings, that supersonic aircraft such as the Concorde used. (Electronic aviation, 2004) Over the past years, many modifications were made to the original straight wing design, after the different company's reviews, developments, and research of existing designs.

Through this investigation, the final aim is to find out what alterations aerospace giants made to the original design, in order to suit their needs; whether that is to increase efficiency, or to allow for an aircraft to travel at near impossible speeds. This is to be completed by a thorough investigation of the different lift and drag characteristics present on an aircraft. A thorough investigation into further aerodynamic properties of the different wings would then follow. Data will be collected via primary data, by means of modelling the wings and wind tunnel testing; as well as secondary research on the related theories.

2. Background knowledge

In aircraft that is moved by a propulsion system, via a propeller or a jet engine, there are multiple factors that influence the aerodynamic properties of the plane. At any point in time, there are always four forces that act on the aircraft provided that the aircraft is within the flight envelope, with an angle of attack below 10-15° (Cutler & Liber, 2005, p.30): lift, drag, thrust and weight (Kundu, 2010, p.57).

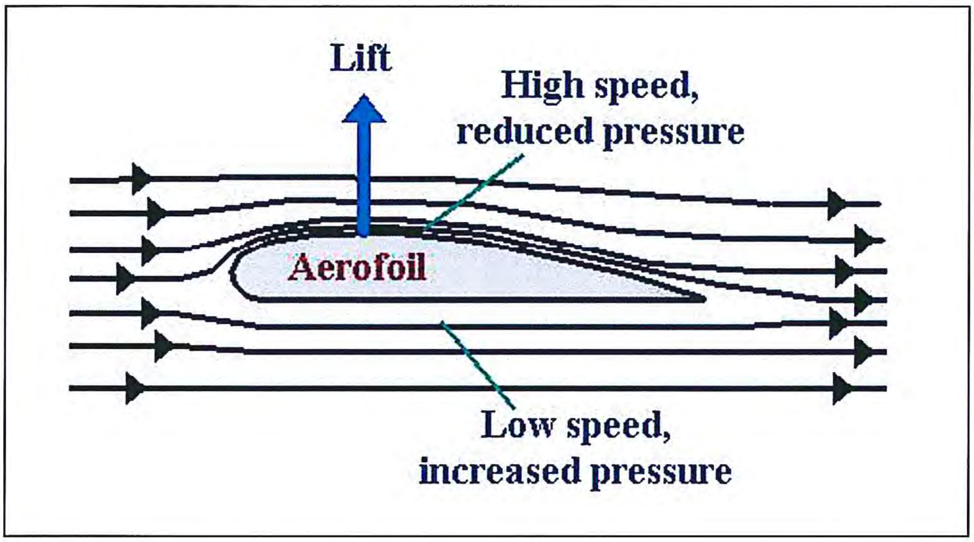
Figure 2.0.1 – Force diagram to show forces that act on a plane in flight



The main focus of this investigation is to look at the lift and drag characteristics of the aircraft. Both thrust and weight will be ignored in this investigation, as the former mainly focuses on the engines of the plane; whilst the latter on the size of the wing, and the materials the wings are made of.

Flight is allowed due to the upward force of lift, which is perpendicular to thrust, and opposite to weight. This is permitted by the cross-sectional shape of the wing, which is known as an aerofoil. (Kundu, 2010, p.58) The shape of a conventional aerofoil allows for the upper surface to be larger (longer) than the bottom. When the air hits the leading edge of the wing, it "splits" into two components. One component deviates to the top surface, whilst the other to the bottom surface. However, according to Bernoulli's Principle, the air molecules from both surfaces arrive at the trailing edge of the wing at the same time. It can therefore be deduced that due to the increased distance, the air molecules on the upper surface travel quicker, hence are more spread out, and therefore generates less pressure. The relative reduction in pressure at the top allows for the wing and hence the aircraft to lift, providing that there is enough airflow, or air speed, as seen in figure 2.0.2. (MIT, 1997)

Figure 2.0.2 – Diagram to show how lift is generated via Bernoulli's principle



(The Engineer, 2011)

Owing to the shapes of various wings, there are also force components that reduce efficiency and oppose the permission of flight. This physical resistance against the on-coming air is known as drag (MIT, 1997). There are multiple types of drag, but all can be divided into two categories: induced drag and profile drag. (Roskam, 2000, p.15)

Induced drag or drag-due-to-lift can be split into vortex drag and wave drag. For the purpose of this investigation, only vortex drag would be examined, as wave drag has minimal effects at low speeds. (Covert, James, Kimsey, Richey & Rooney, 1985, p.158)

Airflow on the underside of any wing always has a higher relative pressure than that of the upper surface in flight, which allows for the lift of an aircraft. This high pressure causes the horizontal movement of air underneath the wing. As the wing has a definite end, the air doesn't have a definite direction beyond the tip of the wing, and hence moves upwards, and curls around the tip of the wing on the upper surface. This movement is known as a downwash, and the drag component is the energy consumed by this. (Kundu, 2010, p.71)

Profile drag on the other hand, is caused by two smaller components, namely, form drag and friction drag. (Torenbeck & Calvert, 2009, p.120-121) Friction drag, which is also known as "skin-friction drag", is caused by the direct contact between the aircraft's skin, and the surrounding air, which is known as the boundary layer. This boundary layer acts as a blockade as an aircraft flies through air. (MIT, 1997) A good analogy of this is described in the Massachusetts Institute of Technology's "Theory of Flight" website states that friction drag, or viscous drag in air is like "the flow of water along a swimmer's body [which] creates a frictional force that slows the swimmer down".

Form drag is the separation of air flow when an aircraft collides with an air "block". This separation causes a wake behind the aircraft, as there isn't normally enough kinetic energy on the skin's boundary layer to allow for the air flow to proceed further along the wing.

3. Investigation

3.1 Hypothesis 1

For the purpose of this investigation, the following hypotheses have been suggested.

> Hypothesis 1: Swept wings have a lowered drag component in comparison to conventional straight wings, allowing for better fuel efficiency and hence are used for planes in service for longer haul flights.

Justification: Most aircraft that were built for the purpose of passenger transport over long distances have incorporated the use of swept wings, ranging from early jet-powered long haul aircraft such as the Boeing 707; to the "jumbo-jet", the Boeing 747 (Pike, 2012). Even more modern aircraft such as the Boeing 777, which uses the world's most efficient wing, utilizes the swept wing as the basis of the design.

Figure 3.1.1 – Image of the swept wings utilized for the Boeing 777

(Lee, 2010)

It is understood that in the transonic speed regime, in which most commercial long haul flights fly at, aircraft may meet problems such as subsonic wave drag or compressibility drag. With the aid of the curvature of the wing's upper surface, the air molecules flow slightly quicker on the top surface in comparison to the bottom. The increased velocity on the upper surface of the wing may, at times, generate a high local air velocity. This local velocity may be in the supersonic speed range, whilst the true air speed, in this case we take the rate in which the fuselage of the aircraft hits the oncoming air, may still be in the transonic or even the subsonic speed range.

This variation in relative speed causes a "shock", which can then interact with the boundary layer, which is the thin layer that surrounds the aircraft's wing, and cause a "premature flow separation". This flow separation then adds to the profile drag that the aircraft already experiences, increasing the overall drag. (Kundu, 2010, p.281)

However, it is known that swept wings are designed to reduce this form of drag, but also has the disadvantage of generating less lift as a result. (Desktop Aeronautics, Inc., 2007)

Figure 3.1.2 – Image of wind tunnel

The school has a Scantek wind tunnel which is capable of measuring lift and drag parameters at variable speeds.

Making: To test the theory that swept wings produce less drag in flight, high impact foam models had to be created, precisely following the specifications (in ratios) as given by the working drawings. This would allow for an accurate prediction of the actual lift and drag characteristics in real world conditions, when the system is tested in a wind tunnel, which can be seen in figure 3.1.2.

The first step of the making was to find the technical drawings of the appropriate aircraft (see Appendix A). This investigation focuses on 3 aircrafts: the Boeing 747-100 which flew for the first time in 1969 (Pike, 2012); the De Havilland Beaver DHC-2 which had its first flight in 1947 (Canada Aviation and Space Museum, n.d.); and the Aérospatiale-BAC's Concorde (this will be looked at in hypothesis 2), which first flew in 1969 (Gordon, 2002). These aircraft were chosen as their period of development was all within a 20 to 25 year period, between 1947 and 1969, hence the technology that was used in developing the designs remained fairly constant.

The Boeing 747 was chosen as it presented one of the world's most iconic types of wing: the swept wing. It is widely used on wide-bodied commercial aircraft, and the data collected would be useful to give an insight to the reasons of the use of these types of wings. The Concorde was also chosen as it was one of the most famous supersonic aircraft, and was in fact the first passenger aircraft to reach Mach 2(Channel 4, 2010). Finally, the De Havilland DHC-2 Beaver was chosen as it had one of the most simple and conventional designs of straight wings.

Figure 3.1.3 – Images to show the making process of the model wings

The working drawings of the 3 test aircrafts' wings (see Appendix A) were found, and were scaled down to meet the size limitations of the wind tunnel. The size of the test area of the wind tunnel was found to be 160x200x200mm (WxLxH) (see Appendix A). However, as a margin for error, the final maximum dimensions used were 150x150x200mm (WxLxH).

After the reduction in scale, the drawings were printed out. The top, side and front views were separated, cut out and stuck onto pieces of high impact modelling foam. These pieces of foam were previously cut to the rough dimensions. By using a scroll saw, the rough outline of the wings were cut out, and with the aid of multiple files, sand paper, the belt and disc sanders, the final wing models were created.

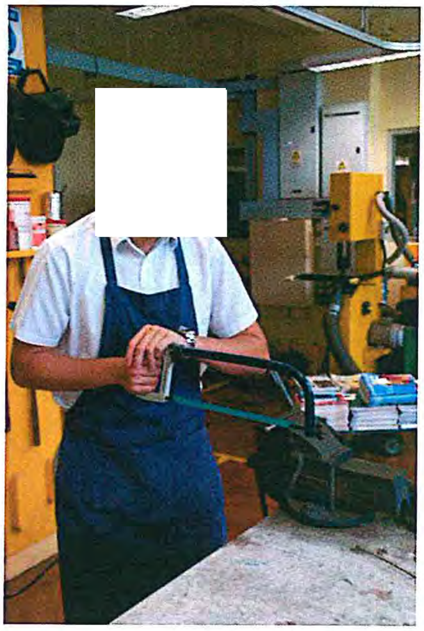
Figure 3.1.4 – Image to show the "chord-line testing" of the 747's swept wing

To measure the accuracy of the model aerofoil's shape, the quality of manufacture was assessed from multiple dimensions including the chord length and thickness. In addition, a further test on the wing sweep angle of the 747 was performed. It is known that the wing sweep angle of a 747-100 is

37.5° (Civilian Aviation, 2008). On a conventional aircraft, the wing sweep angle would be measured from the quarter chord line on the wing, to a virtual line which is perpendicular to the wing centre line. However, as the wing centre line isn't present, the line that is formed by the flat surface intended for attaching the wing onto the fuselage was used. This angle was measured to also be of approximately 37.5°. These tests were both passed and the chord lines were drawn on the models, to show the accuracy. The final accuracy test completed, prior to the wind tunnel test was a visual confirmation of the final product against the working drawings used.

The wing models then had a small hole with a diameter of 6.5mm drilled, allowing for them to be screwed into the test bed ready for the final wind tunnel testing. Meanwhile, the screws had to be cut down to a considerably shorter length, in order to reduce the amount of exposure in relation to the screw, as this would prove to affect the lift and drag results. This was completed via the use of a metal vice, and a hacksaw as seen in figure 3.1.5.

Figure 3.1.5 – Image to show the reduction in screw length by means of sawing



The screws were found to be of an excessive length, and hence were reduced in length via the use of a hack saw and a metal vice.

Testing: The 747's swept wing was first tested. It was decided that the model would be tested at various set air speeds, as this would allow a holistic comparison of the lift and drag characteristics between the wings in the subsonic and transonic speed regimes. It was therefore also decided that the DHC-2's wing would also undertake the tests in the same conditions. To keep the test fair, an angle of attack of 5° nose up would be used. This would allow for the wing to remain within the flight envelope, which is below 10-15°, preventing the separation of flow, otherwise known as stalling, affecting the lift and drag data(Cutler & Liber, 2005, p.30).

The following table shows the results of the testing for the 747:

Table 3.1.6 – Table to show the lift and drag results of the 747 at various relative speeds

Aircraft	Force Component	Relative Speed (v)								
		8.5			5			2		
		R1	R2	R3	R1	R2	R3	R1	R2	R3
Boeing 747-100	Lift	3.5	3.2	3.5	1.5	2	1.5	0.2	2	0.2
	Drag	3.2	2.9	2.8	1	1	1	0.1	0.1	0.1

As expected, the amount of lift and drag increases along with the air speed. However, anomalies can be detected from the table. For instance, the readings R2 for lift of relative speed 2 was significantly higher than expected at "2", whilst the others being at "0.2".

Meanwhile the test of the DHC-2's wing was scheduled a week later, as there were multiple interruptions regarding school activities. However, during this interim week, the machine broke down, and a problem with the drag meter developed. According to the lead technician at the school, Mr Draeger, there was an "unhappy spot in the bearings" of the drag meter, and hence the meter would not return to the "0" position when the air speed read "0". The data collected from the test had, consequently rendered useless.

In the face of this unfortunate setback, the alternative of secondary sources was employed for the purpose of this investigation. On the grounds of "fairness" between the two types of wings, the Boeing 747's lift and drag data would also come from secondary sources.

It was realized later on, that due to the lack of research resources, the lift and drag data for the DHC-2's wing was unavailable. However, it was known that the Beaver's wing was developed from a NACA Series 4, 4416 wing model (Lednicer, 2010), hence the data for this model was used.

Results and conclusion: The maximum lift coefficient (C_l) of the 4416 wing was found to be 1.725. By dividing this value with the maximum (L/D), which in this case is 48.786 (Airfoil Investigation Database, 2012), the drag coefficient (C_d) is given (Benson, 2010). The C_d value comes up as 0.03536.

This process was also applied to the Boeing 747's wing. The Boeing 747 used BAC 469 to BAC 474 wing models. These two wing designs were based on the BAC XXX wing model (Lednicer, 2010), which had a maximum C_l of 1.231. Completing the same process of division by the maximum (L/D) of 41.464 (Airfoil Investigation Database, 2012), the C_d is found to be 0.02969.

From the results, it can be seen that the C_d of a swept wing is significantly less than that of a straight wing. This means that by altering the quarter-chord line's angle and hence the wing sweep angle, a wing's drag can be reduced, increasing the efficiency of the wing.

3.2 Hypothesis 2

Hypothesis 2: In comparison to the straight wing, delta wings will have a lower (L/D) at takeoff and approach speeds.

Justification: An aerofoil or wing with a low lift-drag ratio means that the operational efficiency is low. This is due to a high amount of drag, relative to lift, hence requiring a high amount of speed to sustain flight (Davis, Niven, Thomson & Young, 2003, p.10.125). The theory implies that delta wings such as the one the Aérospatiale-BAC's Concorde uses, has this problem. In order for the aircraft to accelerate to targeted flight speeds up to Mach 2, sleeker, thinner, "slender deltas" were developed. These aircraft allowed for flights at speeds in the supersonic speed regime, however were notorious for their bad lift characteristics at low speeds (Whitford, 2007, p.174).

At low speeds which are used for take-offs and landings due to safety requirements (Kundu, 2010, p.282), the delta wings use the principle of vortex lift (Gordon, 2002) in order to sustain flight. For conventional aircraft, vortices or "lift-dependent induced drag", are produced at the tips of the wings, which in turn slows down the aircraft, and hence reduces the (L/D) (Kundu, 2010, p.71). However, due to the shape of the delta wing, and a high sweep angle, the vortices that normally cause vortex drag on a wing tips, are actually located on the upper surface of the wing. This position allows for the vortices to increase the relative velocity of the air stream on the upper surface, hence causing a lowered pressure up top, and therefore lift (Kroo & Alonso, 2006).

Making: The model of the De Havilland Beaver used to test hypothesis 1, was also intended for use in this part of the investigation. Meanwhile, the working drawings of the delta wings used by the Concorde were sourced.

The original plan was for the Concorde's delta wing to be made using the techniques as stated in hypothesis 1, however, it was soon evident that this would be near impossible. It was realized that the illustrations as seen on the cited document didn't reveal the true shape of the Concorde's wing. In fact, there were multiple impressions on the wing's leading edge and underside that couldn't be seen in the drawing, but could be seen by the naked eye in images, such as figure 3.2.1. It was therefore decided that the statistics required would also be gathered from secondary sources.

Results: Unfortunately, due to the malfunctioning of the wind tunnel as stated above, no reliable results were collected for the NACA-4416 or the Concorde's delta wing model.

Secondary data was therefore found and used. The maximum (L/D) for the NACA-4416 is known to be 48.786 (Airfoil Investigation Database, 2012). Meanwhile the maximum (L/D) for Concorde is found to be 4 (Orlebar, 2004, p.116).

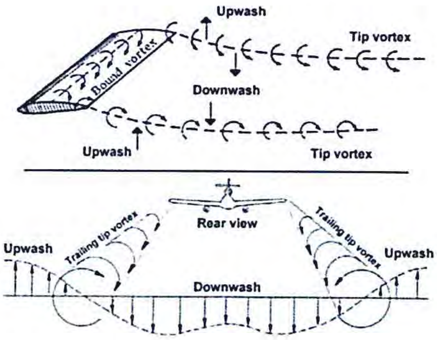
Analysis and Conclusion: The (L/D) for the NACA-4416 is a high 48.786 in comparison to the Concorde's 4. This is due to two main factors: the shape of the wing, the different types of drag that affect the aircraft at approach speeds which are in the subsonic speed regime.

The Concorde adopts the shape of a slender delta wing, which is very thin and long. By reducing the thickness of the wing, as well as distributing the cross-sectional area appropriately, it allowed for the aircraft to accelerate to twice the speed of sound (Roskam, 1997, p.75). This is done by reducing the amount of wave drag (also known as compressible drag). However, due to this shaping of the wing, there were poor lift characteristics, and was mainly supported by additional vortex lift. Vortex lift is created when the highly pressurized air from the under surface of the wing moves sideways to the edge of the wing. The air then rises upwards beyond the edge of the wing forming an up-wash. This up-wash causes a circulatory movement of the air, causing a downwash on the upper surface of the wing. These vortices created allows for air to be

Figure 3.2.1 – Image to show complex shape of the Concorde's delta wing

(AviaFilms, n.d.)

Figure 3.2.2 – Illustration to show the creation of vortex drag on a conventional straight wing



(Scott, 2005)

accelerated on top, allowing for a lesser pressure, and hence lift (Kroo & Alonso, 2006).

However these vortices also prove to be a source of drag, as the "energy consumed by the downwash appears as lift-dependent induced drag" (Kundu, 2010, p.71). Despite this induced drag, the amount of lift the vortices create outweigh the amount of drag produced, allowing for flight at high angles of attack (Roskam, 1997, p.75).

Furthermore, without the high-lift devices such as leading edge slats and trailing edge flaps on the Concorde, the lift-drag ratio at low speeds is reduced even further. Aircraft such as the DHC-2 are equipped with flaps, which are components that "expand" the wing, putting the aircraft in a "dirty-configuration". This in turn increases the area of the surfaces of the wing; allowing the creation of even more lift, and hence allowing for flight at lower speeds, during take-off and landing (Kundu, 2010, p.282).

Conclusion

The research question for this investigation was **"How does the design of a wing affect the lift and drag characteristics of an aircraft?"**

From the results of the investigation, it can be concluded that the design of the wing controls all the aerodynamic properties of an aircraft. If the wing or aerofoil's parameters are altered, the lift and drag characteristics of the aircraft will change drastically.

The results from the investigation concluded that drag can be reduced by a slight sweep angle. This was investigated in the experiments testing hypothesis 1, where the Boeing 747's aerofoil as well as the NACA-4416's aerofoil were tested. It was found that the NACA-4416's aerofoil produced a higher drag coefficient of 0.03536, whilst the Boeing 747's aerofoil produced a lesser drag coefficient of 0.02969.

Meanwhile, the drag of a wing can be increased by the transformation of the shape. For instance, by increasing the length of the wing, and implementing a high sweep angle (forming a delta shape), the drag coefficient would increase significantly.

The lift to drag ratio can also alter depending on the parameters, as explored in hypothesis 2. The example tested in this investigation was the delta wing on a Concorde. The results from the Concorde's wing were tested against the NACA-4416's data. It was found that due to the high drag coefficient induced by the vortex drag, which are formed by the "upwash" and resultant "downwash", the lift to drag ratio for the delta wing was a mere 4 at approach speeds. This is significantly lower than the 4416's 48.789.

The profile of the wing was also the culprit for the lowered lift at low speed, and caused the aircraft to be reliant on vortex lift.

To conclude, aerodynamic alterations are made to wings for different purposes. These alterations may allow for aircraft to fly farther and burn less fuel; or fly faster but less economically. Whatever the purpose, aerodynamic considerations are always taken into account, as even the smallest of alterations to the design may cause the lift and drag characteristics of an aircraft to change significantly.

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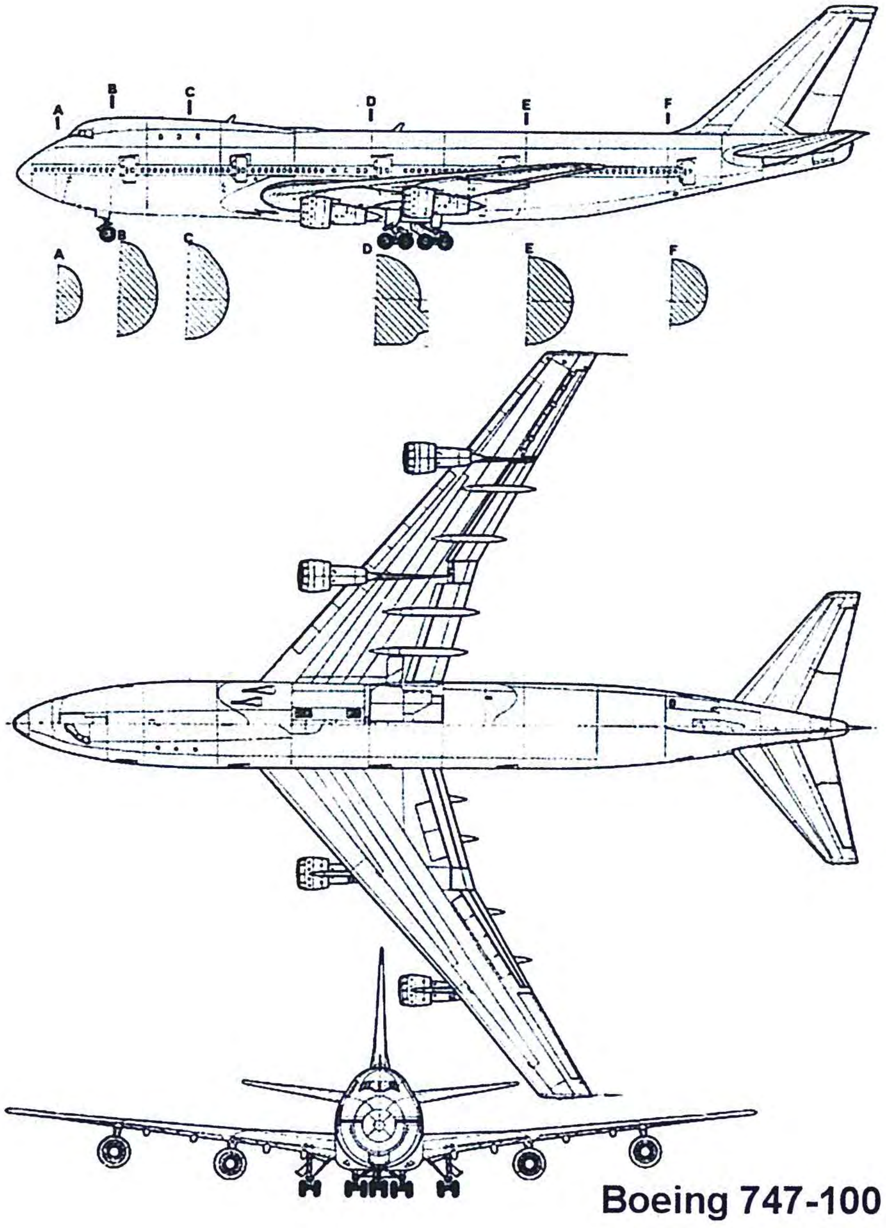
Appendix

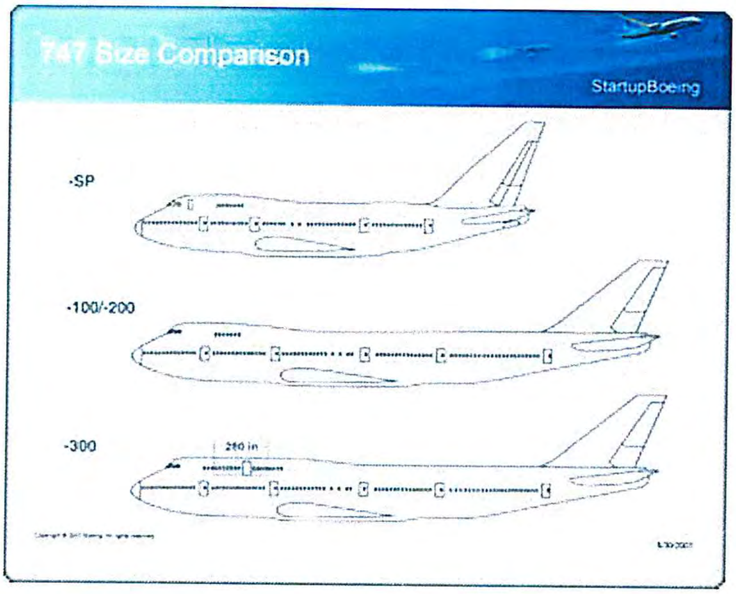
Appendix A

Figure 5A.1 – Working drawing for the Boeing 747-100



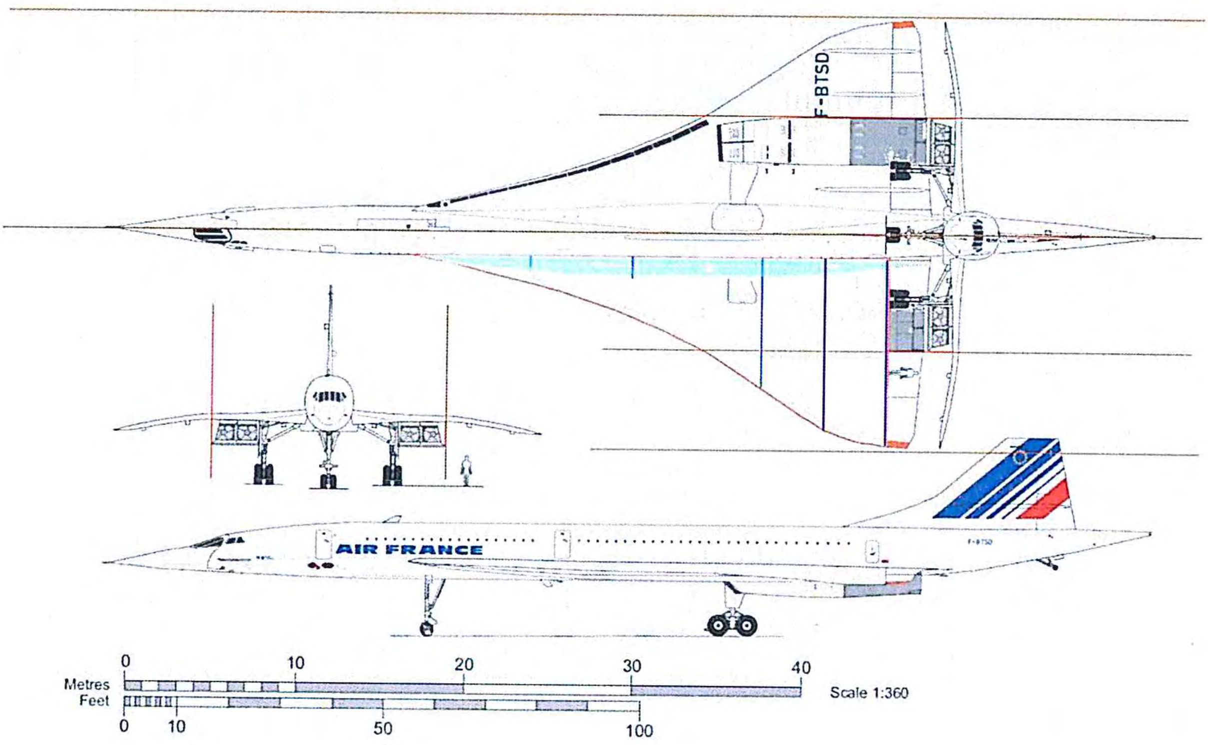
(Lindeman, 2010)

Figure 5A.2 – Illustration to show the shape of the airfoil used on a Boeing 747



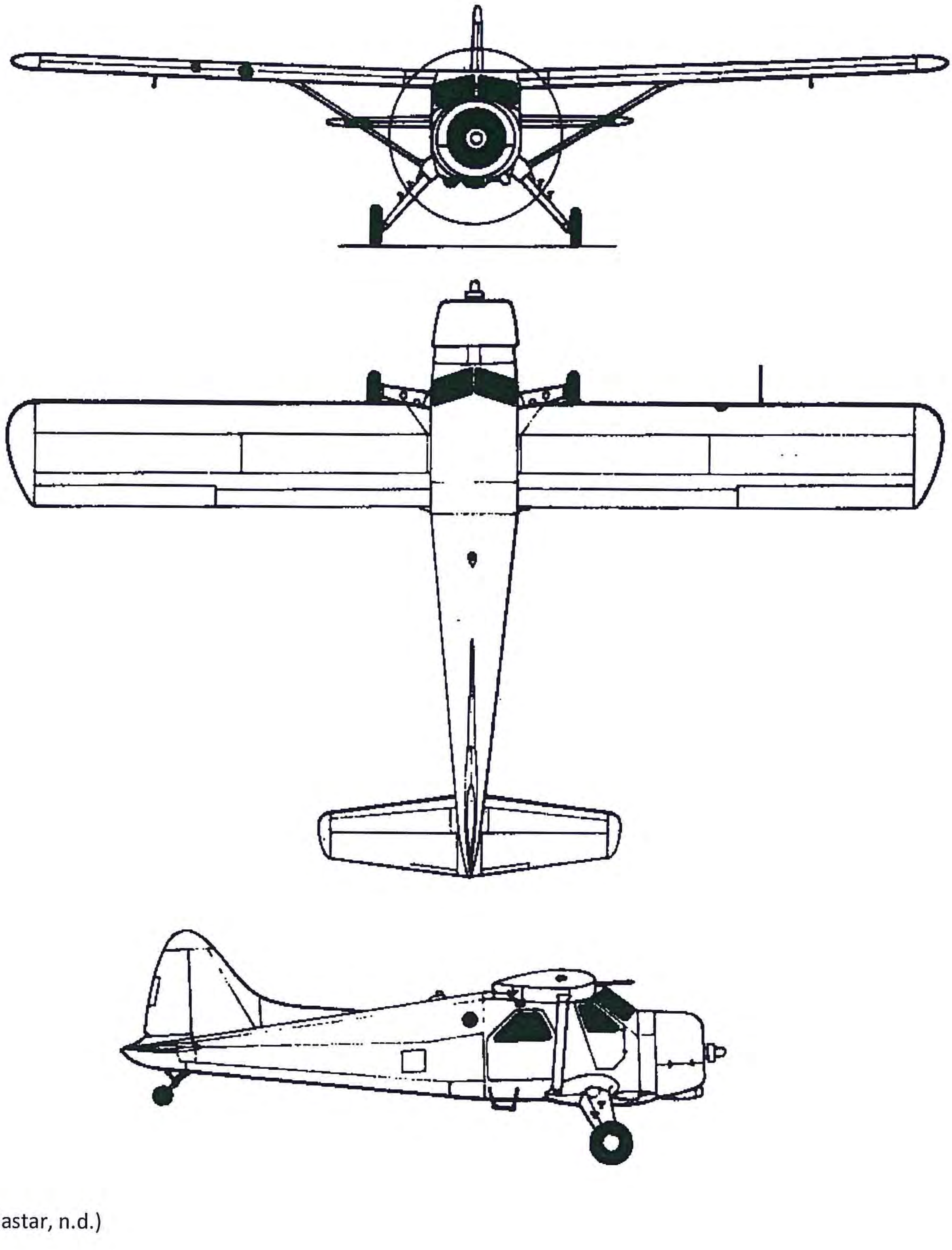
(Boeing, 2007)

Figure 5A.3 – Working drawing for the Aérospatiale-BAC Concorde



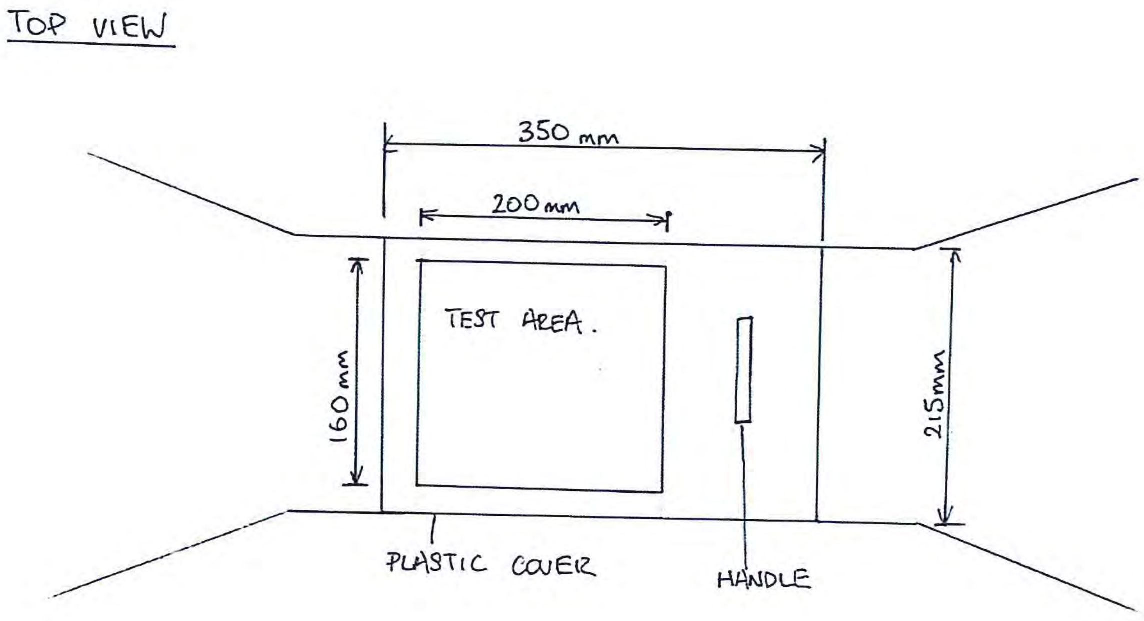
(Wattflyer, n.d.)

Figure 5A.4 – Working drawing for the De Havilland DHC-2 Beaver



(Aviastar, n.d.)

Figure 5A.5 – Illustration to show the configuration of the in-school Scantek wind tunnel



Appendix B

Terminology

Lift – Lift is the upward force which is caused by the difference in relative pressure between the upper and lower surfaces of the wing, providing that there is enough air speed (Kundu, 2010, p.63).

Drag – Drag is the force that opposes thrust, and hence motion. It is created by various factors, such as the shape of the wing (Torenbeck and Calvert, 2009, p.58).

Lift-drag ratio (L/D) – An (L/D) is a ratio that allows for the efficiency of any wing to be presented. A higher (L/D) value means a more efficient design (Davis, Niven, Thomson and Young, 2003, p.10.125).

Wing sweep angle – The wing sweep angle is the angle between a virtual line which is drawn perpendicular to the wing centreline, and the quarter-chord line (Kundu, 2010, p.77). This is shown in figure 5B.1.