Adaptive wing design for a morphing mav biology essay

The wing design of a Micro Air Vehicle is to be designed to aid in the assessment of earthquake damage. The MAV is required only to be powered by an electrical motor, limiting flight time and endurance/range, and must be able to fly to the scene quickly and efficiently. Therefore, the analysis of the wing structure is two-fold: 1) having an efficient wing design for cruise (faster) flight and 2) having an effective loiter (slower flight) wing design. The main methodology in ensuring the optimal wing structure would be to design two aerofoils with an actuator which will morph the wing dependant on the different requirements.

The software package DESFOIL, on the University of Sheffield intranet, is considered a friendlier user interface for the original XFOIL package created by MIT Professor Mark Drela to aid in the understanding of low speed aerofoil flow solution. However, since XFOIL contains a less than friendly interface, DESFOIL, a MATLAB based software, creates a friendlier user interface, enabling aerofoil analysis to be more easily understood.

NACA Aerofoils

Since NACA aerofoils will be the predominant choice in attaining the aerofoils for our MAV, this section will concentrate on providing a breakdown on the key aspects of such aerofoils.

The 4 digits associated with the NACA aerofoil provide information as to the physical structure of the aerofoil. The four digits are broken up as such

The first number offers information about the maximum camber as a percentage of the chord length.

The second digit provides information as to the position of this maximum camber as a function of the overall chord length (in tens of units)

The final two digits provide information on the maximum thickness of the aerofoil as a percentage of the overall chord length, as a percentage.

Thus, it can easily be seen that the chord length is pivotal in determining the correct NACA aerofoils.

Centre of Pressure and Aerodynamic Centre

Other important aerofoil characteristics are the centre of pressure and aerodynamic centre. If we consider them individually, we can attain a clearer picture of their importance.

Starting with the centre of pressure, it is known that the positioning of this point changes with lift, namely it moves towards the leading edge as lift increases. However, using this same theory, it can be understood that this centre of pressure can move outside of the aerofoil geometry. More specifically, at low levels of lift generation, the pressure centre can be behind the aerofoil.

Such a parameter is important to understand since it allows for trimming of the potential aircraft on which the aerofoil will be mounted. The centre of pressure can be calculated using calculus provided a pressure distribution is understood. Since we are dealing with a distribution, the length of the chord becomes increasingly important and it is normal to talk about the pressure as a function of chord length, generally starting with the leading edge.

The aerodynamic centre contains a more direct link with the stability of the aircraft/aerofoil. The aerodynamic centre is the point on the aerofoil where the pitching moment of the aerofoil is independant of the angle of incidence. Understanding of this point is crucial due to its large contribution to the balancing and therefore stability of the aerofoil/ aircraft. Since the majority of aerofoils which will be considered within this journal are cambered, it is interesting to note that the aerodynamic centre is approximately situated at a point ¼ of the chord length.

Drag

When considering drag, the main thought is of a retarding force to motion in a certain direction. The relationship is simple; the greater the drag (retarding) force, the greater impedance on motion. From an aerofoil design point of view, we wish for such force to be as minimal as possible since a lower retarding force allows faster speeds (longer endurance and/ or range) and more efficient flight.

To understand more about drag, we need to understand more about the different components of the force. If we can understand the force’s main constituent parts, this may help us lower the drag our aerofoil experiences.

The drag force can be broken up into several different components. Some of these are

Parasitic drag

Lift induced drag

As we will later calculate, the lift our aerofoil produces will vary depending upon which flight attitude regime we are in i. e. loiter or cruise, and thus the drag each regime experiences will vary. Since this is important in understanding how the aerofoil will react to regime changes, the lift induced drag will be looked at more closely within this analysis.

The concept of parasitic drag is broken into many different parts. Such constituent parts include skin friction and pressure drag. The concept of skin friction comes about due to the interaction of fluid molecules contacting the surface of the aerofoil, bringing local wall shear stresses into consideration. It can thus be seen that the faster the motion of molecules past the aerofoil, the larger wall shear stress. The skin friction coefficient shares an inverse parabolic relationship with the speed of the aircraft

The contribution from pressure drag will be considered in terms of flow separation points further into this report. Such drag will take precedence in the analysis of drag within this report since it provides a more rigorous depiction of the drag at different angles of attack and different DESFOIL accuracy parameters (panel number). Since DESFOIL offers only this type of drag, it will be assumed that this pressure drag is the overall coefficient of drag, when discussing analysis of graphical data. This is a reasonable assumption since the drag values and pressure distributions compliment each other.

Furthermore, since we will later consider the 3D effects of the aerofoil, it is important to note that there will be different drag factors which will increase the amount of drag experienced by the aerofoil.

A major form of drag which the aerofoil will experience while in flight is the vortex drag, more specifically the drag due to the mismatch of pressure along the upper and lower surfaces of the aerofoil. More specifically, this drag arises due to an overspill of high pressure on the lower surface of the aerofoil to the upper surface, which is abundant in low pressure areas. Thus as the aerofoil moves through the fluid, in our case air, this overspill will manifest itself into tip vortex, increasing the drag experience by the aerofoil.

Thus, although only drag will be termed in this journal, there may be separate underlying factors involved.

3D and 2D Calculations

Although DESFOIL is only applicable to 2D aerofoils, adjustments can be made such that the results from DESFOIL can be used within 3D situations. Since we are designing an actual aerofoil, such considerations need to be taken into account, and are during the later parts of this journal.

The importance of using such a program lays in its simulation of the aerodynamics the aerofoil experiences. Therefore, using such a program allows the possibility to determine what coefficient of lift (or, 2D and 3D analysis respectively) and coefficients of drag, subscript’d’, or ‘ D’ accordingly, are needed for optimal flight. As we will determine in this report, optimal coefficients will be calculated and a wing structure designed accordingly.

Design Brief

The following reading is an analysis of the software package DESFOIL on the suitability of difference NACA 4 digit aerofoils on an MAV of certain design specifications. These include

Cruise Speed, = 15

Loiter Speed, = 8

Wing Area, S = 0. 13

We will assume a rectangular planform for our aerofoil. Furthermore, we will assume the aerofoil as the main form of lift, i. e. neglecting fuselage, tail plane or rudder lift generation

Wing Characteristic/ Structure

Lift is defined as the aerodynamic force that a surface produces in the presence of a perpendicular velocity vector. Since lift is defined as a force, , we can assume that lift is some function of the density of the medium it is produced within, , the size of the object producing such a force, , and the before mentioned velocity, Therefore,

(1)

Where x, y and z are unknown parameters defining the relationship outlined in the equation. Through dimensional analysis we can deduce the values of such unknowns.

(2)

(3)

In terms of lift forces, the constant of proportionality is termed the coefficient of lift, deriving the lift equation

(4)

It is also possible to consider a more rigorous analysis of the coefficient of lift taking into account symmetrical and cambered aerofoils, which yield and respectively. However, such equations only apply to thin aerofoils and since the thicknesses of the aerofoils are unknown in this assignment, the generic formulae will be used.

Similarly, derivation of the drag forces can yield an equivalent drag version of equation (4).

(5)

To deduce our optimal lift coefficient, we will assume the lift generated will equal the weight of the aircraft, a reasonable assumption when considering straight and level (cruise) flight and the loiter regime. Therefore, the lift coefficients can be calculated for the respective flight conditions

(6)

Equation (6) yields a cruise coefficient of lift of 0. 285, while similar analysis for loiter conditions yields a lift coefficient, of 1. Since we are initially more concerned with the wing aerodynamics with respect to wing structure (aspect ratio), we will consider the induced drag, , whereby,

(7)

Where e is the Oswald efficiency of the aerofoil, a correctional factor added since the wing shape differs from the elliptical wing used for the derivation, and A is the aspect ratio, calculated by the length to width ratio. To select the best aspect ratio for our aerofoil, the induced drag variation with aspect ratio changes is shown in Figure 1.

It can easily been seen from Figure 1 that an aspect ratio of 5 would be acceptable since there is negligible variation in terms of the two dimensionless concepts. However, if we consider this in terms of the actual MAV, an aspect ratio of 5 would yield a span of 0. 8m and a chord length of 0. 16m. Evidently, while this is the longest and thinnest allowed in this particular investigation, possible structural problems may occur. However, if we consider the capabilities of the aircraft, there are advantages too.

As Figure 1 has shown the induced drag in flight would be decreased, enabling better endurance and longer range. The structural instability could be overcome by careful selection of materials and designing of the structure. Thus, although problems may arise from such an aspect ratio, these problems can be overcome and do have their own advantages.

Such data allows calculation of cruise and loiter Reynolds number and Mach number to be calculated.

Figure 1: Induced Drag and Aspect Ratio relationship

(8)

(9)

Similarly, and.

Panel Number

Since DESFOIL is the primary tool in determining which aerofoil will be used and its aerodynamic characteristics known, it would be wise to research the capabilities of the software and which system (panel number) to use to ensure the results obtained are of relevant accuracy. Another important aspect of using DESFOIL is the time taken for results to be determined. This will be analysed next.

If we consider the effects of panel number on the lift, drag and pressure distribution respectively, we can clearly see a relationship shown in Figures 2, 3 and 4.

Considering an angle of incidence of 10 degrees, it is evident to see that the most accurate results come about with the higher panel numbers. Since the maximum panel number within DESFOIL is 280, it would seem this would be the optimal choice. However, upon closer analysis, it is the time taken for such accurate results to come back from the software, which is of greater importance. For example, a panel number of 280 will provide the most accurate answer, but also take the longest to deduce.

Therefore, if we consider the (negligible) variation of values, we can deduce that a panel number of 180 is significantly lower, thus, allowing quicker results, but still retains a high level of accuracy. For example, for the lift coefficient, 180 yields 1. 0012, while 280 yields 1. 0028. Thus the accuracy difference is negligible.

Figure 2: Variation of Lift with different panel number on NACA0012 aerofoil

Figure 3: Variation of Drag with panel number on NACA0012 aerofoil

When analysing the pressure distribution, fewer panel numbers were considered, since the graphical representation would have become severely hard to differentiate between the different graphs.

On the other hand, the before mentioned negligible differences is perhaps clearer in Figure 4. With the panel number at 280, the pressure distribution is most smooth, allowing finer details to be seen, which would otherwise be lost in lower panel numbers. Thus, a panel number of 180, the lowest without losing significant accuracy, is optimal.

Figure 4: Variation of Pressure Distribution with panel number on NACA0012 aerofoil

Reynolds/ Mach number

So far, we have considered only the cruise aspect of the MAV. Since the aircraft will experience loitering stages also, analysis must be considered into different Reynolds and Mach numbers. Both of these are necessary in understanding the aerodynamics of the aerofoil since they both alter the way in which the aerofoil will react to airflow. For example, consideration of transition points, the onset of turbulent flow, boundary layer thickness and laminar flow needs to be understood to optimise the aerofoil design.

Therefore, changes in the behaviour of the aerofoil/ airflow must be modelled and simulated within DESFOIL. For further understanding of such phenomenon, XFOIL will be used to pictorially show the effects of Reynolds number and Mach number on boundary layer, amongst other sets of information.

More specifically, larger Reynolds and Mach numbers will be taken into consideration to visualise compressibility effects. To observe such results, i. e. how changes in density with regards to the pressure distribution, comparisons will be made to show how the compressibility effects (large Reynolds/ Mach number values) alter the characteristics/ performance of the aerofoil.

An angle of attack of 10 degrees was considered when undertaking the computations in all examples.

Incompressibility/ Compressibility Effects

Figures 5 and 6 visually show the variation of the boundary layer with a high Reynolds and Mach number.

If we consider Figure 5, we can see the specific values of coefficients of lift, drag and pitching moment at the angle of attack mentioned before. Another helpful mode shown within Figure 5 is the description of the change in boundary layer over the length of the chord of the aerofoil. This pictoral view shows the general formation of turbulent flow from laminar flow. As will be seen later in the report, there is a relationship between the boundary layer thickness and the Reynolds number. This relationship is important to note since a thinner laminar boundary layer ensure lower drag. Again, this concept will be further investigated later.

Figure 5: XFOIL graph showing pressure distribution along aerofoil

Figure 6: XFOIL graph showing variation of other aerofoil characteristics

Reynolds Number

Mach Number

Cl

Cd

lift/drag

1000000

0. 4

1. 083

0. 01965

55. 13

169412

0. 04

1. 0266

0. 03469

29. 59

90353

0. 024

0. 9415

0. 05289

17. 8

Figure 7: How lift and drag vary with different Reynolds and Mach numbers

From Figure 7, we can see the direct impact the differing Reynolds numbers and Mach numbers have on the generation of lift and drag. Quite clearly, as the Reynolds/ Mach number decreases, so does the coefficient of lift, and thus lift generated. Also of significant importance is the increase in drag with decreasing Reynolds/Mach number. Due to these variations, the lift to drag ratio also decreases.

However, it is important to note that the results are non-linear. This non-linearity can be explained from the transition from incompressible flow to flow whose density changes with respect to the pressure distribution. Thus, such characteristics cannot be extrapolated or calculated; they must be experimentally defined, or computationally simulated, since consideration of compressibility effects adds complexity to calculations.

Boundary Layer Analysis

Although there is little difference between the values of lift coefficients (in the first two examples), there seems to be a drastic difference between the lift: drag ratios. Since the coefficients of lift are similar, varying by less than a magnitude of value, the only possible change must come from the drag experienced on the aerofoil.

Experimental data, treating the aerofoil as a flat plate, shows that as the Reynolds number increases, the boundary layer thickness decreases, shown in Equation (10).

(10)

Thus, a decrease in the Reynolds number causes a larger boundary layer around the aerofoil, which in turn causes a greater disturbance to the free stream air.

Since the boundary layer cannot handle a large adverse pressure gradient without separation, the higher values of Reynolds number cause separation earlier, even though they have thinner, boundary layers. This is due to greater adverse pressure gradients which are responsible for the larger values of lift coefficients attained. The separated flow causes larger amounts of drag, which is obviously undesirable, since the flow is no longer uniform along the chord. Once the pressure gradient exceeds a critical point, the boundary layer will separate from the aerofoil, therefore reducing the magnitude of the pressure gradient, reducing lift generation. Therefore, the lift: drag ratio decreases as drag will increase upon separation.

The drag experienced at higher Reynolds numbers is still considerably smaller than the drag experienced at lower Reynolds numbers due to the thickness of the boundary layer. Although separation of the flow is a factor with regards to drag, the boundary layer thickness, as seen in Figure (7) using Equation (10), is a larger factor.

Since this separation point (transition from laminar to turbulent flow) is an area of interest with regards to the amount of drag experienced by the aerofoil, Figure 8 shows the movement of such a point with regards to the Reynolds number.

The black lines only show the separation points on the upper surface of the aerofoil since this is the surface of most interest.

Figure 8: Transition point. 1) Re= 1000000, M= 0. 4 2) Re= 169412, M= 0. 04 3) Re= 90353, M= 0. 024

At this point it is important to note that the DESFOIL parameters were changed to ensure a completely accurate result from the simulation. To ensure the accuracy was maximised, the transition ‘ detection’ was 100% the length of the chord, and not simply the default 20%. This allowed DESFOIL to look throughout the whole length of the chord for the transition/ separation point as opposed to the default 20%.

As we can see, for the same angle of attack, the higher Reynolds/ Mach numbers cause the separation point to be significantly closer to the leading edge. Similar XFOIL graphs were constructed as that in Figure 6 for the other Reynolds/ Mach numbers. From Figure 6, we can see that at an angle of attack of 0 degrees, there is a separation point at 0. 637, i. e. 63. 7% away from the leading edge as a function of the chord length. When the Reynolds number is 169412, this separation point is 91% as a function of the chord length, while the loiter Reynolds number remains laminar at 0 degrees angle of attack.

Geometries

If we consider other three dimensional geometries with respect to the drag each produces, we can understand why an aerofoil is an optimal shape in terms of reducing drag.

Figure 9: Drag values for various 3D geometries

If we consider streamlining any given shape, we can possibly reduce the amount of drag experienced, as shown in Figure 9, by an order of magnitude. For example, if we consider the sphere, hemisphere and teardrop shapes, although all have the same frontal geometry, it is the streamlining of the teardrop which contributes most to a significant reduce in drag, due to the prolonged attachment of the airflow. Since the airflow after the sphere/hemisphere is suddenly separated (due to the non gradual geometry behind the shape), there is a significant amount of drag experienced.

This is why Figure 5 depicts such a prolonged attachment of the airflow, only becoming separated towards the trailing edge of aerofoil.

To further reinforce the advantageous effects of streamlining, Figure 10 shows the geometrical differences which can be obtained with intelligent streamlining.

Figure 10: Two different geometries with the same aerodynamic drag force

Lower Aerofoil Surface

Another important feature found from graphs similar to Figure 5 highlights the relationship between the angle of attack, Reynolds/ Mach number and flow over the lower wing section. It was found that at lower Reynolds numbers, the flow is relatively laminar across the length of the chord length. This makes sense at high angles of attack since the underside of the aerofoil has a larger wetted area.

Possible further investigation and research may lie in determining the flow over the lower surface of the aerofoil in negative angles of attack. Perhaps such an investigation will help understand the landing/ descending section of a flight path. It may be interesting to learn whether separation points play such a major role on the lower surface as they do on the upper surface, in terms of lift and drag. Such understanding can provide insight into painting a complete picture of the airflow surrounding a wing.

Furthermore, since a NACA0012 aerofoil was considered giving all the results mentioned previously, changes in airflow with varying NACA aerofoils could help determine a more complex relationship. For example, as thickness, camber and camber position change, how does the transition point vary on the underside of the aerofoil?

Such variations are made within the next section with regards to the overall lift and drag. However pressure variations could be conducted in a similar fashion.

Designing using DESFOIL

Since DESFOIL allows the user to design, test and evaluate their own chosen design (one of the many reasons it was chosen for undertaking of this particular investigation), it is important to understand how the different parameters affect the aerofoil characteristics. From this, we can deduce what the optimal aerofoil for our application could be. Furthermore, it allows for reinforcement of aerodynamic theory into the reaction of airflow over changing geometries of aerofoils. This could be seen as a measurement of DESFOIL's accuracy in its simulations. If its simulation results were to vary from known aerodynamics, then the software's validity would be questionable. Throughout the analysis, therefore, the aerodynamic theory will be called upon to explain the results given from DESFOIL.

Since the software allows for three different design features, it was deemed necessary, to gain a full understanding, to adjust and examine one parameter at a time and comment on the results obtained. Since different values of lift were optimal for the different stages within our flight path, both the cruise and loiter conditions were looked at.

From the template aerofoil NACA0012, the thickness was the first parameter to be changed. Figures 11 and 12 below graphically shows the variation in lift and drag over the four different aerofoil thickness's chosen.

Cruise Conditions

Figure 11: Lift variation with different NACA aerofoils thicknesses

Figure 12: Drag variation with varying thicknesses

Firstly, the cruise conditions will be investigated.

As we can see from the figures above, the thickness of the aerofoil plays an important role in determining such characteristics as stall angle and maximum coefficient of lift. If we consider both graphs simultaneously, we can deduce the thicker the aerofoil, the greater the values of lift can be obtained. This is shown with the increase in coefficient of lift values from 12% thickness to 15-21% thickness. This is down to the curvature of the aerofoil being the main form of lift generation, i. e. the more curved (thicker in this instance since camber position is constant) the aerofoil, the larger amounts of lift generated, within limits. Also, nose shape effects help the generation of high lift coefficients. Furthermore, it is important to note that the thinner aerofoil has also stalled significantly harder than the thicker aerofoils. Since stalling is undesirable, perhaps thicker aerofoils would be best for use in the chosen aerofoil.

Concentrating on the graphs from a drag point of few, we can again see that thinner aerofoils are undesirable due to the drag they produce/ experience. The sharp rise in drag experienced by the thinner NACA0012 aerofoil is complimentary of the stall it experienced at an angle of attack of 13.

Furthermore, it is important to note that there are slight variations in the small angle of attack region with respect to lift and negligible difference in the corresponding drag section.

Since a definitive relationship was deduced from the thickness investigation, it was reasonable to continue the designing experiments. Next, the camber thickness was investigated.

Figure 13: Lift variation with angle of attack with different camber thicknesses

Figure 14: Drag variation with angle of attack with different camber thicknesses

From the above figures, certain relationships can be deduced between the camber thickness and the effect such parameters have on the lift and drag experienced on the aerofoil.

Firstly, let’s consider the adverse effects on the lift and drag, shown here by the NACA-2012, whereby the ‘-2’ denotes a negative camber. From Figure 13, we can see a significantly lower lift attained flight with an earlier stall, which compliments Figure 14, whereby the drag significantly increases due to the separated flow resulting from the stall. For the other three aerofoils shown, the aerodynamic drag force experienced by each has negligible difference, since all follow the same shape. The differences can more obviously be seen through analysis of Figure 13. Here, we can see the larger the camber, the greater values of lift can be obtained. However, it is important to note that only the NACA4012 aerofoil does not experience a stall. On the other hand, the other two positive aerofoils, while although experiencing a stall, do not stall extremely harshly, and so a stall of this kind, while although not optimal, can be considered negligible in terms of lift generated.

The camber position was investigated next

Figure 15: Lift variation with angle of attack under different camber positions

Figure 16: Drag variation with angle of attack under different camber positions

As we can see from the above two figures, the effect of camber position is not as drastic as the other previous analysed parameters. From Figure 15, we can see the highest lift is attained by the NACA4212 aerofoil, although all the aerofoils have the same similar low angle of attack lift generation. It is only towards angles of attack greater than 7 where there is greatest deviation. On the other hand, it can also be seen that the NACA4212 aerofoil, while giving the highest lift value, also stalls. As mentioned before, this is undesirable. From a drag perspective, the NACA4212 aerofoil performs best towards larger angles of attack however performs worst at low angles of attack. Depending on where the greatest emphasis needs to be placed upon the cruise aerofoil conditions, this may be an important factor.

Chosen Cruise Aerofoil

Since we have analysed the effects of the three different parameters within DESFOIL, we can now evaluate what lift and drag characteristics we want from our chosen aerofoil. Since the actual aerofoil will be 3D, we need to take into consideration 3D effects. For this instance, we are going to assume the 3D coefficient of lift is 90% of the 2D coefficient of lift, namely,

(11)

One reason there is a decrease in the change from two dimensional to three dimensional bodies is the appearance of an extra plane, i. e. the z plane. Thus, the lift generation needs to distribute the lift over three planes instead of two. Thus resulting in less lift overall. Therefore, we can calculate a coefficient of lift of 0. 3167 to be found using DESFOIL. Taking what was found from the above investigation, various NACA aerofoils were tested. The final aerofoil chosen was the NACA2615 aerofoil for reasons clearly shown using Figure 17.

Figure 17: NACA2615 aerofoil characteristics

From this figure, we can see the optimal design characteristics we want from our cruise aerofoil. These characteristics include a significantly low drag, as compared to the lift generated, which can be seen as a direct result of no stall being present. Furthermore, if we consider the lift we wanted to generate, namely 0. 3167, we can see this aerofoil manages to attain such lift at a low angle of attack, something we want from our aerofoil since the quicker the optimal lift can be generated, the quicker the aerofoil will start behaving to optimise its performance. Since this optimal lift is generated at an angle between 1 and 2, the lift: drag ratio was calculated for these two angles. They are 17 and 39 respectively. These high values show the positive performance of our aerofoil in the cruise condition.

Loiter Condition

As we can see from the previous section, a detailed investigation and analysis was undertaken to establish the best NACA aerofoil for our cruise purposes. If we now go on to consider the loiter condition, there are certain parameters which need to be considered, namely the 2D lift we wish to aim for, at the lowest angle of attack, to find the optimal aerofoil.

As shown in the previous section, the thickness, camber and camber position were all varied individually and the resulting effect on the lift and drag analysed. Using Equation 11, we can calculate the required lift (needed to be found in DESFOIL) as 1. 11.

Firstly, the thickness was adjusted. It was found, just like the cruise condition investigation that an increase in thickness resulted in higher levels of lift being attained. However it was also found that the aerofoils under loiter conditions tend to stall, regardless of thickness. However, the greater the thickness the higher angle of stall. Since all aerofoils tested stalled, the drag associated with each was indicative of this phenomenon. It is also important to note that the aerofoils tested were the NACA0010, NACA0012, NACA0018 and NACA0021.

Considering the position of maximum camber next, it was found that the NACA4212 aerofoil stalled significantly earlier than the NACA4012, NA