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ON THE FLUID DYNAMICS OF ADAPTIVE AIRFOILS

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ABSTRACT

This paper discusses issues and practical requirements for an adaptive wing in relation to currently available technology. Adaptive wings offer many benefits, but a viable wing will require research into several areas, including selection of initial and perturbed airfoil shapes, steady and unsteady aerodynamic analysis of adaptive airfoils, and methods for real-time shape control of an adaptive wing system. An overview of adaptive wing history is briefly covered, including some recent developments. Development considerations for an adaptive wing system are then discussed. Aerodynamic performance and stability should be considered in the context of the wing's structural integrity and aeroelasticity. Particular attention should be paid to the unsteady nature of the flow, as standard quasi-steady flow analysis techniques should be abandoned due to the rapid changes in wing shape and motion. Due to the large number of variable and measured parameters, an advanced control system is required to relate the flight conditions with changes in geometry. Issues related to adapting wings to various aircraft scales will be discussed, specifically micro aerial vehicles (µAVs), unmanned aerial vehicles (UAVs or RPVs), full-scale aircraft, and ornithopters.

INTRODUCTION

Adaptive wings, i.e., wings whose shape can be altered in flight, have the promise of revolutionizing aeronautics. Recent research has been conducted into adaptive airfoils from both theoretical and engineering standpoints. While the benefits of an airfoil whose geometry is variable in flight is readily seen, the current state-of-the-art lacks the stringent requirements for practical application. This is exacerbated since the complexity of the problem often calls for examinations of potential adaptive systems from a single perspective rather than considering the physics of the whole system; viz., aerodynamics, structural dynamics, and control. This includes work such as the development of flexible airfoils whose thinness precludes structural development with current materials or wings with bulky and heavy actuation systems which negate the benefit of the adaptive design. However, recent developments have shown that a viable adaptive wing is in the foreseeable future.

The primary motive for altering wing geometry is to improve airfoil efficiency in off-design flight regimes. This concept is a standard implementation in most modern aircraft designs and takes the form of flaps which change the wing area and/or effective camber. A polymorph wing (variable planform) and variable pitch or incidence are also proven methods of wing adaptation. Adaptive concepts have taken many forms and names, including deformable, flexible, and active, in addition to those previously mentioned. In this paper, however, we will use the term *adaptive* to indicate an airfoil whose actual (as compared to effective) profile can be altered during flight.

The ideal use of an adaptive strategy allows the wing to vary its geometric parameters in flight during encounters in situ of changing flow conditions such as wind speed or direction. As much of the governing principles of the unsteady fluid/structure interactions are unknown, extensive research into the physics is necessary, including the dynamics of series adaptive paneling, the actuation and control of an adaptive wing in flight, and real-time unsteady aerodynamic measurement and analysis. It is the dynamics of the fluid/structure interface that interest us here, primarily the aeroelastic transient coupling of the varying airfoil parameters and the unsteady flow. As the wing changes geometry, the flow will rapidly follow these changes. However, since the flow is a continually evolving structure, the altered flow field can interact with the wing in a nonlinear fashion. To determine the desired singular or periodic variations in wing geometry a priori, it will be necessary to first understand the underlying physics. The number of variables results in an inordinately large parameter space which requires the use of simulations to be used in tandom with any experimental investigation.

Several issues need to be investigated for the development of an adaptive wing system, including selection of initial and perturbed airfoil shapes, unsteady aerodynamic analysis of an adaptive airfoil, and artificial neural networks and fuzzy logic control systems for real-time shape control of an adaptive wing system. Aerodynamic performance and stability should be considered in the context of structural integrity and aeroelasticity. Particular attention should be paid to the unsteady nature of the flow, as standard quasi-steady flow analysis techniques should be abandoned due to the rapid changes in pitch-up, pitch-down, and harmonic wing motion. Due to the large number of control inputs, a complex control system must be used to relate the flight conditions with changes in geometry.

HISTORY

Wing Warping: The First Adaptive Wing

The first significant use of adaptive wing technology was developed and used by the Wright Brothers in their *Wright Flyer* aircraft at the turn of the century (figure 1). Their wing warping concept was the first effective element of lateral control, essentially changing the camber of the aircraft wing to increase or decrease lift (1; 33). Due in part to its complexity, however, (and in part to the strict patent enforcement by the Wrights on their technology), the modern method of aircraft control, viz., the aileron, was developed soon thereafter. Regardless of these events, a method other than wing warping would have been developed. While wing warping worked well for the relatively light and flexible aircraft of the day, as aircraft were built to carry more weight and fly at faster speeds, stronger wings were developed to accommodate these structures. The revelation during the first World War that thicker airfoil sections were better at creating lift than the thin profiles used at the time also gave aeronautical engineers more leeway in designing wings with greater stiffness and strength. Thus, a decade after the flight of the first powered aircraft, the idea of the adaptive airfoil as a practical application was essentially dead.

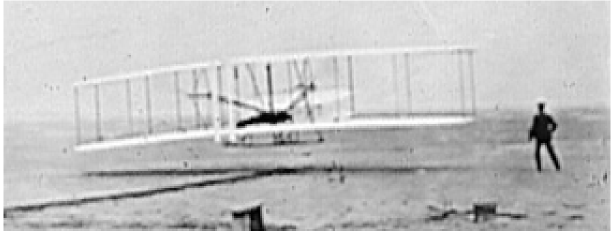

Figure 1. December 17, 1903.

The Wright Flyer used wing warping for lateral control. (Library of Congress Wright Photo 2A13.)

Recent Developments

Adaptive wing technology returned to aircraft design through incremental steps. These were primarily in the form of gross adjustments to wing orientation, such as the invention of variable pitch in propellers (1924) or variable sweep wings (1952). Both of these concepts were developed to increase the efficiency of the airfoil in a given flight regime. Additional attempts at altering wing efficiency included momentum transfer devices such as blowing or suction slots or wings that polymorphed with telescoping or folding tips. Even aircraft with oblique yawing wings have been demonstrated to be buildable and flyable. Though each of these concepts showed some success in improving airfoil efficiency, only the basic lift devices (flaps, slats, spoilers) have seen widespread application. However, these strategies still treated the wing as a rigid structure and could not fully utilize the idea of wing adaptivity.

One of the early departures from the philosophy which treated aircraft wings as rigid structures discussed the advantages of structural tailoring in aircraft (34). This approach takes advantage of characteristics such as structural anisotropy and elastic coupling to enhance a particular structural response. This approach to airfoil design has been demonstrated to yield significant benefits. It provided the framework for subsequent investigations that added active elements to improve upon the already significant benefits of structural tailoring. Further studies examined in detail the interaction between aerodynamic forces, structural forces, conventional control forces, and an additional control force arising from inclusion of active materials in the wing structure (10). A mathematical foundation was presented that argued that the inclusion of active materials in the wing structure could be used to advantage to increase wing speed divergence, reduce gust loading, and change lift effectiveness. It is clear that an ability to control these wing characteristics in a practical fashion would lead to a wing design which is beneficial to aircraft performance.

Active elements were added later to enhance structural tailoring effects (2). This work was a largely experimental study where the static shape of a prototype F-14 wing cross-section was controlled with an array of linear actuators that acted as both wing spars and actuators to control wing shape. The stated goal of this study was the reduction of shock-induced drag in transonic cruise and multi-DOF shape control was demonstrated that could potentially address this problem.

Modeling of aeroelastic structural tailoring and adaptive wings (those that incorporate active materials) were more fully examined using a thick walled composite beam representative of the structure of a modern aircraft wing (20). The wing model included anisotropy and coupling to allow structural tailoring and active layers to provide shape control. The results of this extensive modeling effort indicated that the combination of structural tailoring and adaptive wing shape control can improve the vibrational and static aeroelastic response of aircraft wings.

The papers mentioned above represent an overview of the early work in adaptive wing modeling. This area has matured to the point where significant experimental verification work is now taking place. Recent tests of a piezoelectric actuator driven adaptive wing were used to demonstrate active flutter control (27). Also discussed were tests investigating alleviation of vertical tail buffeting and wing shape control using piezoelectric actuators applied to load-bearing structural members. Development of wind tunnel models and results of wind tunnel tests of adaptive wing models have also been demonstrated (16; 18). Both investigations lend credence to the basic concept of the adaptive wing as a practical design option for an aircraft wing. An adaptive airfoil design designated the Dynamically Deforming Leading Edge (DDLE) airfoil varies the leading edge radius in flight by stretching its thin composite skin (3). The primary objective for this development is to achieve effective flow control over the airfoil through the reduction of strong adverse pressure gradient that leads to wing stall.

Recent investigations into flexible wing architectures have shown the possibility of their use in adaptive wing technology (17; 30). Due to the nature of the system, however, where the airfoil is typically a curved flexible arc section more akin to a sail than an airfoil, several disadvantages arise. Most notably is the inability to sustain large lifts due to the lack of wing stiffness. The inability to actually develop a practical wing system which is adaptive as opposed to merely flexible is another primary difficulty since no room exists for the location of actuators. The analytical methods developed to study such wings are also useful in the study of more rigid wings, however.

DEVELOPMENT CONSIDERATIONS

Several areas need to be carefully considered for the development of a practical adaptive wing, including aerodynamics, structural dynamics, and wing control. These will be covered in turn, following a discussion of the benefits of adaptive wings.

Consider the simple wing geometry as shown in figure 2. The rectangular wing has a span b, chord c, area S, and aspect ratio $AR = b^2/S = b/c$. This geometry will be used throughout the remainder of this paper as a baseline.

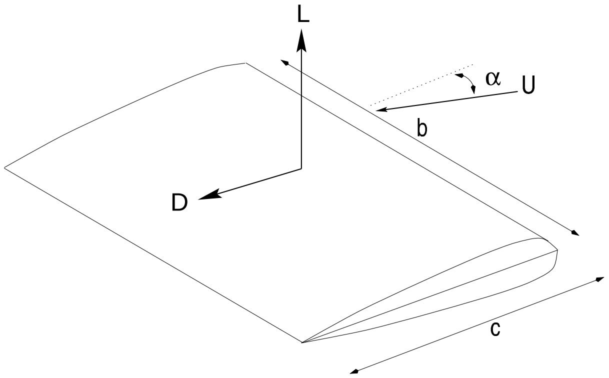

Figure 2. Wing geometry.

Rectangular wing with span b and chord c at an angle of attack α and free-stream velocity U.

Benefits of Adaptive Wing Technology

For an adaptive wing to be a viable design option, some of the following criteria must be as good or better than that of a conventional wing:

1. efficiency
2. maneuverability
3. control
4. weight
5. cost

Currently, none of these parameters offer significantly better performance than a traditional static airfoil. Weight and cost concerns will surely improve as research into adaptive technology continues; the rapidly advancing fields of artificial neural networks and fuzzy logic will aid in the area of adaptive wing control. However, two primary benefits are readily apparent with adaptive wings: improved efficiency and enhanced maneuverability. These are discussed briefly below.

Efficiency For a given wing, we are principally interested in maximizing the airfoil lift L and minimizing the drag D, or alternatively, maximizing the lift-to-drag ratio, L/D (also written as the ratio of lift coefficient C_l to drag coefficient C_d, or C_l/C_d, defined below). This is often taken as a measure of the wing's overall efficiency. This ratio, however, is often highly dependent upon not only the wing geometry but the given flow conditions as well. These flow conditions are typically expressed as dimensionless parameters such as the Reynolds number Re and Mach number M. A given airfoil profile will have vastly different lift and drag characteristics over the possible ranges of Re and M for a given aircraft. Thus, airfoils are typically designed for a narrow range of flow conditions for optimum performance. Alternatively, one could design an airfoil that adequately operates over a wide range of flow conditions but does not perform well in any.

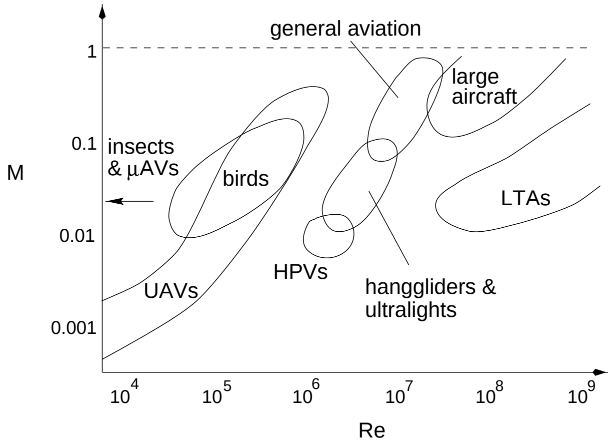

Figure 3. Reynolds number and speed envelope. *Re* versus *M* for a wide-range of flying objects. (Adapted from Lissaman, 1983.)

Figure 3 shows various ranges of operation for man-made and natural flyers. Note that each has a fairly narrow bandwidth in both *Re* and *M*. (The sole exceptions in this graph are UAVs (unmanned aerial vehicles) and LTAs (lighter-than-air vehicles) both of which cover a large category of aircraft built for a variety of purposes.)

The lifting capability of an airfoil is defined by the lift coefficient

$$C_l = \frac{L}{\frac{1}{2}\rho U^2 S} \tag{1}$$

where ρ is the fluid density and U is the wing velocity relative to the surrounding medium. Likewise, the drag coefficient is given by

$$C_d = \frac{D}{\frac{1}{2}\rho U^2 S} \tag{2}$$

Furthermore, we can separate the drag into two primary components, the induced drag D_i (drag to due lift) and all other drag D_o (friction, wake, etc.). The induced drag can be estimated in terms of wing geometry by

$$D_i \approx C_l^2/\pi AR \tag{3}$$

(A factor dependent upon wing shape has been dropped for convenience.)

In level and steady flight, the generated thrust T must balance the drag D and the generated lift L must balance the vehicle weight W, or

$$T = D \qquad L = W \tag{4}$$

This simply shows that increasing L (or C_l) results in the ability to lift a vehicle of greater weight. The resulting power requirements can then be derived from the relation

$$P \sim TU = DU = (D_o + D_i)U \tag{5}$$

Substituting D from equations 2 and 3, we can write

$$P \sim \frac{1}{2} C_d \rho U^3 S + \frac{2W^2}{\pi \rho b^2 U^2} \tag{6}$$

which shows that a minimum power exists for a specific U. The cubic term represents the power required to overcome increasing air resistance at increasing velocity while the hyperbolic term represents the power required to generate enough lift at low speeds to keep $L = W$. This is the velocity of maximum economy.

The point of minimum total drag can be determined from the point at which the D_i and D_o are equal. From equation 6, this can be shown to be

$$D_{min} \sim 2W\sqrt{\frac{C_d}{2\pi AR}} \tag{7}$$

Since $L = W$, this corresponds to L/D_{max} conditions and is the region of maximum aerodynamic efficiency. Since the drag increase hyperbolically at low velocities, it is typically more economic to fly at greater than minimum drag speed than below it. As typical aircraft spends most of its in a high velocity cruise mode, the wing profiles are selected with this in mind.

Maneuverability Aircraft maneuverability is difficult to codify and is defined with a number of quantities. We will use a single example to illustrate the effect that adaptability would have on maneuverability.

One important indicator of aircraft performance is the turning radius, R. For most types of aircraft, it is advantageous to minimize R to as much as a degree as possible. This is especially important in fighter aircraft and is frequently used as a measure when comparing varying designs.

In a level circular turn, the vehicle is banked so that the lift vector is no longer vertical, resulting in an acceleration of the aircraft towards the center of radius. Since the vehicle must maintain constant altitude, the vertical component of the lift must remain equal to the weight W, dictating that L/W must now be greater than unity. From a simple force diagram, it can be seen that

$$R = \frac{U^2}{g\sqrt{(L/W)^2 - 1}} \tag{8}$$

where g is the gravitational acceleration. The equation shows two relations with which to minimize R: decrease U and/or increase L/W. As indicated above, however, L/D drops as U drops below the minimum drag point, decreasing the wing efficiency. This is not the best way to decrease R given a static wing profile. Although, equation 8 can also be written as

$$R \approx \frac{2}{\rho g C_l}\left(\frac{W}{S}\right) \tag{9}$$

Thus, increasing C_l and decreasing the wing loading W/S are two methods of improving the turning radius. When R decreases, then wing efficiency and economy are restricted. To increase performance requires a change in the effective airfoil shape. Modern aircraft typically have a large and fixed W/S, leaving C_l as the primary factor in decreasing R. (Interestingly, the Wright Flyer with a wing loading of 60 N/m^2 will have a smaller turning radius than a F-16 with $W/S = 3500$ N/m^2.)

Aerodynamics

The primary consideration for the development of an adaptive airfoil is aerodynamical. Since an aircraft airfoil has optimum performance at a single speed but must operate over a wide flight regime, altering the airfoil shape in one way or another is often a requisite design consideration; adaptability is an attractive possibility. This is done in current aircraft applications by using lift-altering devices such as flaps, slats, and spoilers to change the effective camber of airfoils.

The primary dimensionless parameter of concern here is the Reynolds number

$$Re = \frac{Uc}{\nu} \tag{10}$$

where Re is based upon the chord with U and c are as shown in figure 2 and ν is the kinematic viscosity of the fluid. One can then presume that

$$L/D = f(Re) \tag{11}$$

Figure 4 shows the variation in L/D performance for various airfoils versus Re as determined by McMasters and Henderson (19; 22). Note that at low Re (in the range of birds, insects, μAVs, and UAVs), 'smooth' airfoils perform worse than 'rough' airfoils. However, the performance of smooth airfoils greatly improves at $Re \sim 10^5$ and exceeds that of rough airfoils. This is primarily due to the difference in the underlying physics at low and high Re.

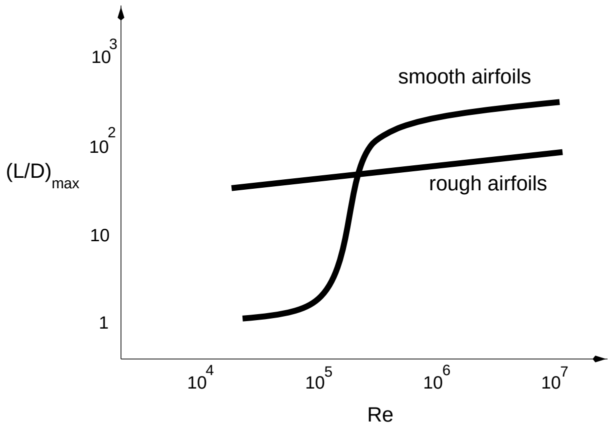

Figure 4. Reynolds number vs lift-to-drag. Rougher airfoils outperform smoother airfoils at lower angles of attack. (From McMasters and Henderson, 1980.)

Figure 5 shows the flow around an arbitrary airfoil at two different angles of attack. The flow around the airfoil at low attack angles is attached to the surface of the airfoil. However, when the wing reaches the stall angle, the flow separates and a dramatic decrease in lift ensues. At low Re, when the flow is laminar, the separation is abrupt. If Re is high or the boundary layer is tripped, the separation is usually delayed since the flow is turbulent. This is why rough airfoils perform better at lower Re than smooth airfoils. One of the primary considerations of airfoil selection is to ensure that the flow remains attached throughout the flight envelope.

Figure 6 shows the variation in lift coefficient C_l for two airfoils vs. the angle of attack α. For a set profile at a given Re and M, the stall angle can be well determined. To increase C_l during such maneuvers as take-off and landing, modern aircraft typically use high-lift devices like leading- and trailing-edge flaps to alter the shape of the wing. This essentially changes the profile of the wing to one which is better optimized at the present free-stream conditions. Figure 6 shows the lift curve slopes for two airfoils, a cambered and symmetric airfoil. The defining difference between these two wing sections is that while the cambered airfoil has a lower stall angle than the symmetric one, the cambered airfoil has a non-zero C_l at zero angle of attack. Thus, the cambered airfoil provides more lift at lower attack angles but stalls sooner than the symmetric wing. An ideal case would be to change the shape of the wing from the cambered airfoil as $\alpha \rightarrow \alpha_{stall}$. If the

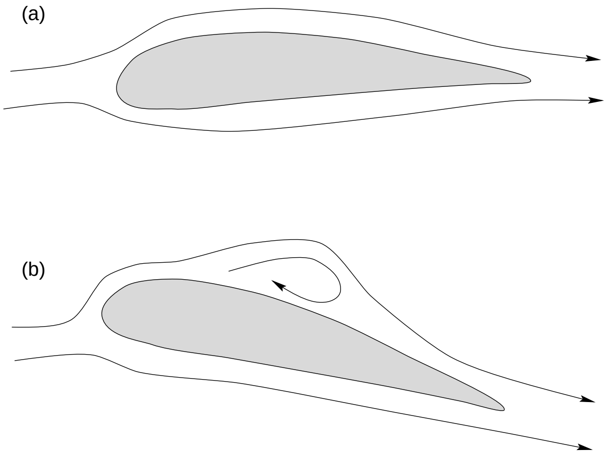

Figure 5. Flow separation.

The formation of the separation bubble at onset of wing stall.

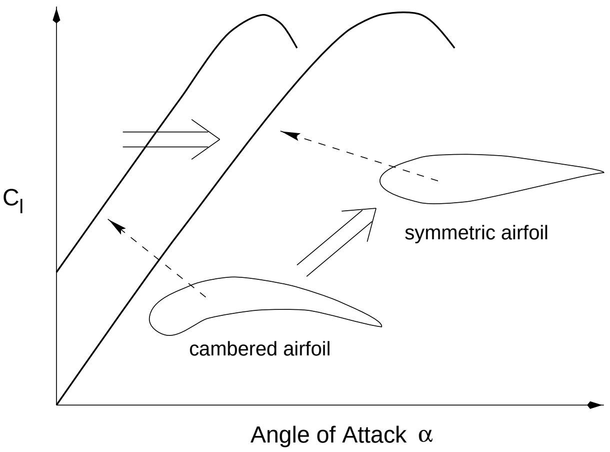

Figure 6. Lift coefficient vs α.

Lift curve slopes for a cambered and symmetric airfoil.

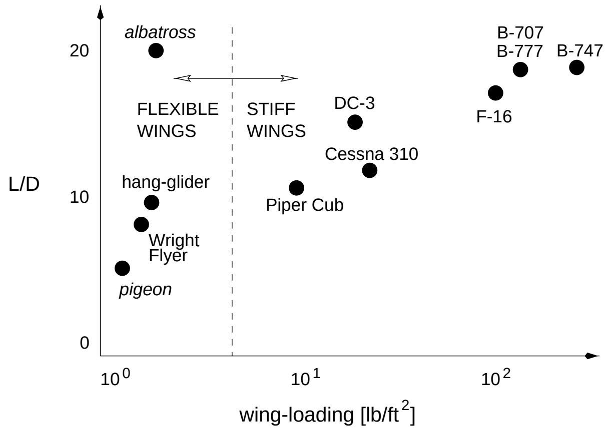

Figure 7. Wing loading vs lift-to-drag.

Most modern aircraft require higher wing loading than is currently possible using adaptive wing technology.

airfoil can assume an arbitrary profile, then one can continually increase the angle of attack while just staying below α_{stall}.

It is worth noting that the angular velocity of the pitching motion, $d\alpha/dt$, has a dramatic effect on flow separation, hence stall. If the motion is oscillatory and at a high frequency, then it is possible to increase C_l above that of the steady $C_{l_{\max}}$. The possible use of unsteady aerodynamics in an adaptive application is thus very attractive. This is discussed in some detail below.

Structural Dynamics and Aeroelasticity

While the primary reason to develop an adaptive airfoil is the aerodynamic benefits, the primary hindrance is the structural considerations. As previously mentioned, early wing development actually favored adaptive structures. Two developments in aircraft technology changed this, however. The first was the realization that thicker airfoils actually created more lift at the current speeds than the thin arc airfoils of the day (e.g., cf. the airfoil used on the Wright Flyer with the Göttingen airfoils used in the late Fokker models of WWI). The second change was the continuing push to carry more weight. This required stronger and stiffer wings. This is demonstrated in figure 7 where L/D is plotted against wing-loading for various aircraft over history. Here, an arbitrary limit has been placed separating ‘flexible’ wings from ‘stiff’ wings. Of course all wings are flexible to some degree, but the heavy aircraft of today require a fairly rigid support structure capable of sustaining thousands of kilograms.

Conventional means of wing shaping require in-wing actuators and additional lifting surfaces. These are typically rigid attachments to the main wing and the profile is altered to an equivalent profile by gross adjustments. These are typically only good in a small range of Re and M. To alter the wing profile in situ, internal actuators can be used to adjust such parameters as camber and thickness, but the adjustments are typically small and the actuators heavy. Thus, the benefits of wing shaping were outweighed by its added weight penalties.

Smart materials offer a more cost-feasible solution to this problem. The most common of smart material actuators are made of piezoelectric materials such as zinc oxide or lead zironate titanate. These are based upon the piezoelectric effect where a force is generated by a piezoelectric material when a differential voltage is applied. These have to be made relatively thick to prevent dielectric breakdown. Piezoelectric actuators can take many forms such as stacks or bimorphs. Both have been used with success in the construction of flaps for airfoils (31). These can be used alone or in conjunction with traditional systems, such as

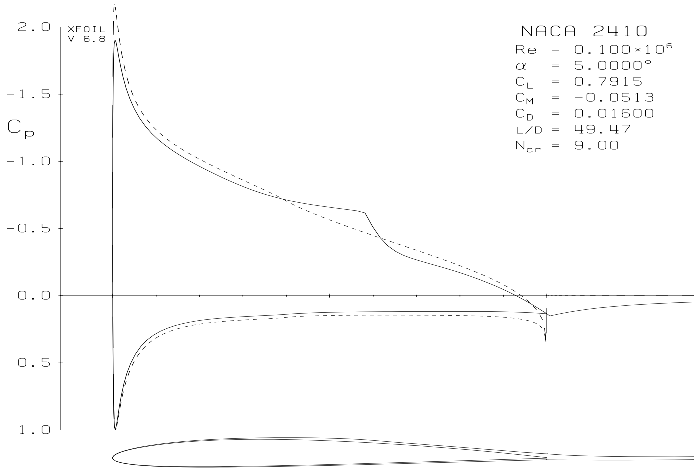

Figure 8. Airfoil surface pressure distribution.

Pressure coefficient determination for a NACA 2410 airfoil with inviscid and viscous formulations from Xfoil 6.8 (8). Real-time determination of such information is required for an ideal adaptive airfoil control system.

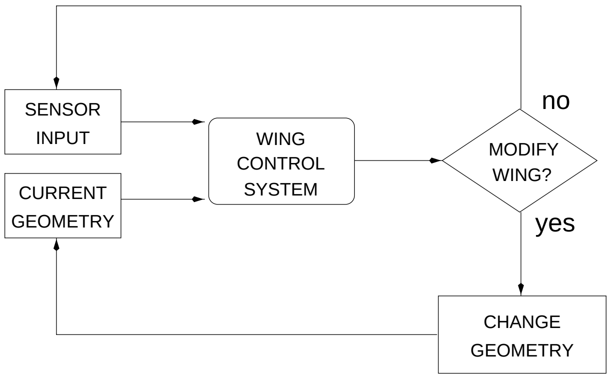

Figure 9. Control functional block diagram.

Control FBD at its simplest level. The purpose of the wing control system is to determine if and what changes should be made from readings of normal aircraft sensor input. This requires extensive training of the wing system with an associated profile database.

hydraulic or mechanical actuators. Piezoelectric actuators have been used by Clement et al. (5) for use in helicopter blade flaps. Other smart materials used in airfoil applications include shape memory alloys (SMA) such as Nitinol. These are metals that change shape when the temperature of the material changes. This can be accomplished by electrical current heating or Joule heating and then allowing the system to cool. Upon cooling, the material returns to its previous unheated shape. This system is particularly suited for use in hydrofoils where cooling is rapid (32). While the same precise control is typically not comparable to a MEMS device, the cost-savings benefits are worth the small reduction in performance.

Control

In essence, airfoil control is profile planning. The control system is responsible for adapting the wing shape for any given flight condition, such as maximizing the lift/drag ratio. A simple control system can be utilized in much the same manner as controlling conventional ailerons: slight alterations in the airfoil profile (camber) give feedback through changes in motion. A truly adaptive system requires a more complex control system, however. Ideally, the airfoil profile can be arbitrarily chosen based upon current flight conditions. The profile can be determined from a pre-chosen map based solely upon known flight conditions or a more complex system can measure and/or calculate the pressure distribution on the current airfoil and optimize the shape real-time (figure 8).

Due to the many variable parameters of an adaptive wing, a complex system to control the aggregate wing is required. Two possibilities include artificial neural networks (ANN) and fuzzy logic algorithms. Artificial neural networks have been used in a number of applications, most notably flow control and design optimization (4; 11; 29). In essence, a neural network is necessary to navigate through the function space of the active wing. An optimization procedure is required to determine the optimum parametric values for a desired wing configuration. The control system should have a hierarchical architecture, consisting of a high level global module that determines the optimal overall wing shape and numerous low level modules that control local wing shapes. The global instruction set should receive flight condition variables as input (e.g., α, Re, M) and determine the corresponding optimal wing shape for the given conditions. The optimal surface shape can then be represented by a parameterized curve equation, allowing the system to learn the mapping from the flight condition parameter values to the curve parameter values. Fuzzy logic algorithms can aid in interpolation between discrete input conditions and extrapolation when a programmed flight envelope is exceeded.

Airfoil control is decidedly non-trivial. E.g., assume that an adaptive wing is divided into 12 control zones for each surface. The airfoil shape can be controlled in each zone. Thus, there are 12 zones on the upper surface of the wing alone and each zone will have numerous possible shapes. For sake of argument, assume each zone has an upper limit of 5 shapes. The parameter space for the wing shaping alone is thus enormous with a total number of possible shapes on the order of 10^8. The use of a neural network or similar system then becomes a very obvious choice.

APPLICATION

As previously mentioned, there are two primary ways of using adaptive wing technology, the large scale (wing shaping) or small scale (boundary layer control). Discussions on possible applications of the former, including μAVs and UAVs, full-scale aircraft, and ornithopters, follow.

μAVs and UAVs

The qualitative aerodynamic characteristics of low *Re* flows are typically vastly different than those normally seen in typical aerodynamic and aerospace applications (19; 24). Slight changes in the flow speed can have large effects on the flow over a given airfoil, most notably severe changes in L/D ratio. The wing shape can be specifically tailored for a certain *Re*, but designing for a larger range of *Re* will degrade performance for a specific wing velocity. Two classes of aircraft fly in the low to moderate *Re* range: Micro Aerial Vehicles (μAVs) and Unmanned Aerial Vehicles (UAVs or RPVs). In the former case, *Re* may range from $10^4 - 10^5$ and lower if hovering/loitering vehicles are considered. In the latter case, *Re* typically increases from 10^5 upwards to 10^6 and higher for the larger faster aircraft. Due to the nature of these vehicles, the technology described herein is well suited for μAV and UAV application inasmuch as the Re range of these vehicles allows the flow to be easily adjusted using wing shaping (30).

Sub-scale air vehicles such as μAVs and UAVs often have the disadvantage of lower lift capabilities due to reduced size but increased weight penalties due to a minimum size of control surfaces. The primary advantage of a μAV is its small size allowing it to go unnoticed on the battlefield. It is ideally suited for covert operations where surprise and advanced intelligence are key components of a successful mission. The size limit of μAVs are typically given as less than 15 cm in maximum length (23; 30). For a standard wing planform, this gives a span of $b = 15$ cm. If a moderate aspect ratio of 4 is assumed and the vehicle is to move at a relatively slow speed, say 10 m/s, an estimate for even high lift coefficients results in lift forces on the order of 0.5 N (0.1 lbs.) or less. This weight leaves little room for equipment, let alone the vehicle structure and powerplant itself. And if the vehicle were to encounter a gust in the same direction as flight, the vehicle would probably crash. Since μAVs are still in the early development stages, issues such as operation, safety, reliability, robustness, affordability, packaging and other operational factors cannot be adequately discussed.

As on option to μAV utilization, an adaptive wing can be installed on a UAV/RPV. This has many of the same characteristics of a μAV, only on a larger scale. UAVs are typically designed for a single mission in mind, usually long-range cruise. For UAVs which have varied mission goals, however, such as loiter, encounter, and then rapid return, the vehicle may experience a variety of flight regimes. An adaptive wing would be an ideal lifting system for such a vehicle. While it would be possible to retrofit an existing UAV with an adaptive wing, it would probably be more cost efficient to design a new UAV around an adaptive wing system.

Full-Scale Aircraft

The adaptive wing also has possible uses in full-scale flight systems. The possibility of reducing drag and increasing lift is of great benefit from both a commercial and military standpoint, primarily by increasing the performance of the vehicle. Thus, an adaptive wing has the possibility for use as a high-lift/high-maneuverability wing. Also, if the wing's performance characteristics are good enough, then it may be possible to design a wing with no control surfaces. In addition, since the wakes of lifting bodies are dependent upon the lift distribution, it may be possible to alter the wakes of aircrafts and marine vehicles through use of adaptive wings. This has benefits in the area of vortex wake mitigation and submarine wake reduction (28). Though the possibility of cost-effectively designing commercial and/or military vehicles with large scale adaptive wing technology is unlikely in the immediate future, various research into using adaptive technology at both the small and large scales is showing great promise for the next century, particularly in the area of boundary layer control (3; 5; 7; 13; 21; 26).

Ornithoptic Propulsion

Since the dawn of man's attempts at flight, he has emulated the methods of natural flyers; viz., birds (15). Numerous research has been performed into the mechanics of natural flyers, including both insect and bird flight (9; 14; 35). While the biomechanics of avians are complex, those of many insects are relatively simple and easy to analyze. An example is shown in figure 10. Note that this simplicity would lend itself well to duplication using adaptive technology.

Scaling determines whether ornithoptic propulsion is efficient for a given weight and length scale. A flyer's weight W is proportional to the cube of the length scale l while the wing area is proportional to l^2 (cube-square law). Thus, one can write

$$\begin{aligned} W/S &\propto W^{1/3} \\ &\propto l \end{aligned} \tag{12}$$

The required power for a given W can be determined from the previously determined relations,

$$\begin{aligned} P_r &\propto W^{7/6} \\ &\propto l^{7/2} \end{aligned} \tag{13}$$

Based on muscle mass arguments (6), the power available to fly-

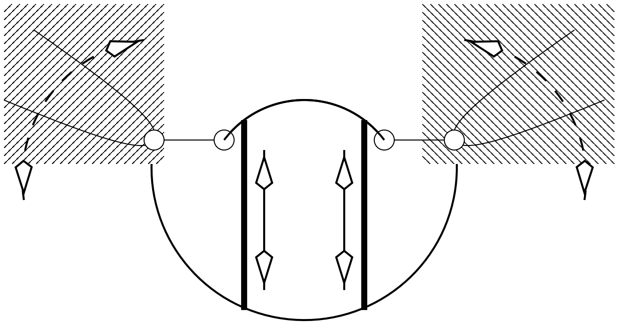

Figure 10. Schematic diagram of insect wing movement.

A simplified schematic of a typical insect wing skeleton is shown. Wing motion is controlled by contraction of interior muscles. The motion in this case is indirect; other insect systems have a direct relationship between muscle movement and wing motion.

ing animals can be shown to approximate the relation

$$\begin{aligned} P_a &\propto W^{2/3} \\ &\propto l^2 \end{aligned} \tag{14}$$

As flyer mass increases, required power will soon overtake available power, not only limiting the maximum possible weight of a flyer but also decreasing the ability of a flyer to climb and/or hover. Hence, larger flyers tend to use soaring as the primary flight mode instead of powered flapping. This also explains why hovering is only accomplished by insects or very small birds, since all of the lift must be derived from wing motion alone.

If we compare the ratio of unsteady lift (i.e., lift derived from flapping) to steady lift (lift derived from forward motion), we find that this quantity can be directly related to the flyer size and weight. Using the flapping frequency f as a measure of this ratio (with the caveat that this will not be an exact relationship), and comparing it with the flyer's length scale l, we see that

$$\begin{aligned} f &\propto l^{-1} \\ &\propto Re^{-1} \end{aligned} \tag{15}$$

This is shown in figure 11. There is essentially a limit to the efficiency of using flapping as a flight mechanism. On the contrary, there is a limit below which flapping is a very efficient flight mode. This has direct applications to the development of μAVs as discussed above. (It may also help answer the question of why nature chose wings over propellers for thrust generation.)

One can envision in the not-too-far-off future man-made bees with adaptive wings and MEMS for flight and using miniature fuzzy-neural computer control systems for control. The primary concern for such a development is the required power.

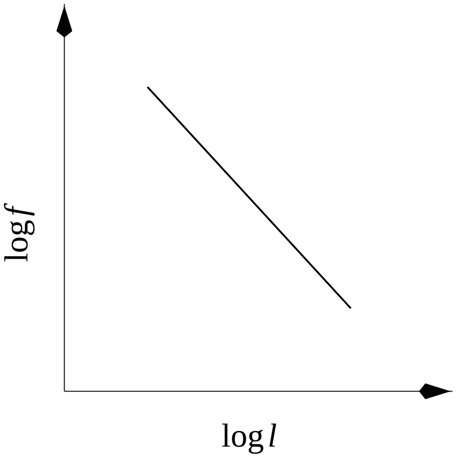

Figure 11. Size vs. flapping frequency.

As the size of natural flyers decrease, the generation of unsteady lift becomes more important to their flight.

SUMMARY

A few of the issues concerning adaptive wing technology have been discussed, including the benefits of shape-changing wings, aerodynamic, structural dynamic, and control considerations, and possible applications. Many items relevant to this topic have not been touched upon, however, such as the use of MEMS for flow control and details of related aeroelastic requirements. The technology shows great promise of yielding realistic possibilities for adaptive wing applications in the very near future.

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