Benefits and design challenges of adaptive structures for morphing aircraft

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ABSTRACT

The purpose of this paper is to discuss the future of adaptive structures leading towards the concept of a fully morphing aircraft configuration. First, examples are shown to illustrate the potential system-level mission benefits of morphing wing geometry. The challenges of design integration are discussed along with the question of how to address the optimisation of such a system. This leads to a suggestion that non-traditional methods need to be developed. It is suggested that an integrated approach to defining the work to be done and the energy to be used is the solution. This approach is introduced and then some challenges are examined in more detail. First, concepts of mechanisation are discussed as ways to achieve optimum geometries. Then there are discussions of non-linearities that could be important. Finally, the flight control design challenge is considered in terms of the rate of change of the morphing geometry. The paper concludes with recommendations for future work.

1.0 INTRODUCTION

Aerospace vehicle design is a never-ending incremental process of adding new ideas with established systems. After a hundred years of development, new designs often look remarkably like the old design with the incorporation of new materials or new electronics. Yet, even after our centennial celebration of flight, expanding mission requirements still give rise to radically new concepts. While these new concepts are exciting for the aerospace engineering community, the customer requires the new system to perform (capability, affordability, reliability, etc) with some increment of benefit over the old systems.

Active structural shape control has been used in a variety of forms since the beginning of controlled flight. Twisting the wing for roll control was used by the Wright brothers, but was soon replaced by the use of discrete control surfaces, i.e. ailerons. As aircraft performance increased, such surfaces tended to have an adverse coupling with the wing flexibility, requiring additional stiffness and weight. The Wright brothers' technique is being 're-invented' in the active aeroelastic wing (AAW) program. In this flight research program, leading and trailing edge devices are scheduled to generate the differential wing twist for roll control(1,2). In conventional applications, leading and trailing edge flaps change the wing camber and Fowler flaps change the wing area, typically for additional lift capability at the low speeds of takeoff and landing. Variable wing sweep angle has flown on a number of configurations to address the conflict between the best value for subsonic and supersonic flight conditions. These examples of using discrete devices like flaps and ailerons are examples of low order shape control. This background leads to the question of how these concepts can be extended with new technology.

Recent advances in structural concepts have the potential to revolutionise operational systems and change flight vehicle design. For example, the use of adaptive systems may enable a multi-mission vehicle

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Table 1
AAF Mission Specifications(3)

Phase	Description
1	Warm-up and take-off at 600m pressure altitude and T = 310K. The fuel allowance is five min at idle power for taxi and one min at military power for warm-up. Take-off roll plus rotation must be = 450m on the surface with a friction coefficient of 0°05. $V_{To} = 1{\cdot}2V_{STALL}$
2	Accelerate to climb speed and perform a minimum time to climb at military power to best cruise mach number and best cruise altitude (BCM/BCA).
3	Subsonic cruise/climb at BCM/BCA until total range for cruise climb is 280km.
4	Descend to 9,150m .
5	Perform combat air patrol loiter for 20 min at 9,150m and Mach number for best endurance.
6	Supersonic penetration at altitude 9,150m and M = 1·5 for 185km.
7	Combat segment model: ● Combat Turn 1: M = 1·6, one 360° 5g turn at maximum power ● Combat Turn 2: M = 0·9, two 360° 5g turns at maximum power ● Accelerate from M = 0·8 to M = 1·6 at maximum power and t < 50s ● Deliver expendables: two AMRAAM missiles, two AIM-9L missils and ½ ammunition Conditions at end of combat are M = 1·5 at 9,150m.
8	Escape dash at M = 1·5 and altitude 9,150m for 46km.
9	Minimum time climb from 1·5M at 9,150m to BCM/BCA.
10	Subsonic cruise climb at BCM/BCA for a range of 278km.
11	Descend to 3,000m.
12	Loiter at 9,150m for 20 min at Mach number for best endurance.
13	Descend and land at 600m pressure altitude and T = 310K. Free roll and breaking must be < 450m on surface with coefficient of friction = 0·18. $V_{TD} = 1{\cdot}15V_{STALL}$

by efficiently optimising the vehicle configuration for any segment of the mission profile or enabling the design of smaller systems that can operate in an urban or canyon environment. The pioneering work conducted to date has greatly improved our understanding of adaptive system capabilities, requirements and system integration issues. To date, however, they have not exploited the potential of distributed actuation systems because they rely on conventional structural configurations.

A new term for shape control has been coined: i.e. 'morphing aircraft structures'. Recently it has been primarily applied to aerodynamic performance. More specifically, recent research is focused on enabling large changes in all the planform geometry characteristics to enable a vehicle to operate much more efficiently over a broad spectrum of flight conditions ranging from cruise and loiter to higher-speed dash. If one considers morphing as a change of state, then morphing aircraft structures can be very broadly defined. Morphing structures can also refer to other attributes of the structure such as optical properties and basic functionality. This paper will focus on the potential benefits from enabling large-scale planform changes for optimising aerodynamic performance across the complete mission, and the design challenges to accomplish them.

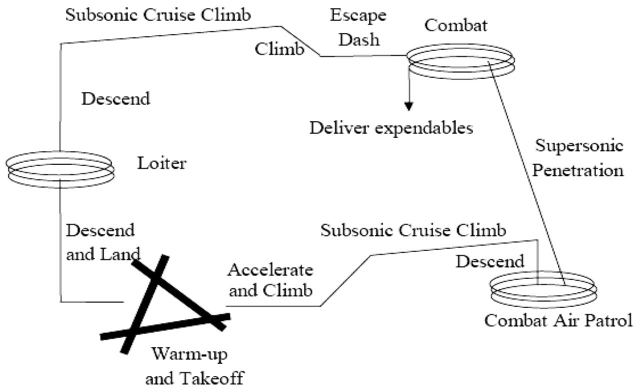
2.0 BENEFITS OF MORPHING GEOMETRY

An initial part of this research was to examine the benefits of using morphing wing technology while simultaneously taking into account other subsystem interactions. 'Morphing wing' is a term given to an aircraft wing or structure that can change size and shape during flight to enable the vehicle to radically change its base performance properties or characteristics. The current goal of using this technology is to create a more efficient and more versatile aircraft by changing the size and shape of the aircraft's wings to achieve the optimum aerodynamic design for each segment of the vehicle's mission. Typical aircraft wings are designed as a compromise to suit all mission segments but cannot achieve an optimum airframe configuration for any individual segment. Wing morphing, of course, will come with a price that must be analysed in terms of the total mission performance. There is additional weight and energy consumption by the aircraft due to the addition of actuators and other materials used to physically morph the wing. The question which must be determined in the context of the overall synthesis/design is: do the improved aerodynamics created by wing morphing offset the penalties associated with the additional weight and energy consumption and yield a more optimum system?

To answer this question, the detailed mission for a notional supersonic air-to-air fighter (AAF) aircraft, as described in Table 1(3,4) and depicted in Fig. 1(3,4), was used since it has segments that would definitely require significant compromise for configurations with fixed geometry. In this research, simultaneous variations in wing geometric parameters were considered, as opposed to the examples previously mentioned, where only a single parameter such as wing sweep or camber, etc, is changed at a time. In the model, the morphing wing is allowed to change wing sweep, wing span, and both root and tip chord lengths all simultaneously for each segment of the mission but within set constraints. These parameters directly affect the aerodynamic properties of the aircraft performance. The model is then optimised in an integrated fashion across the entire mission to achieve an optimal synthesis/design of the AAF which consists of a propulsion subsystem (PS) and an airframe subsystem (AFS-A). The optimisation simultaneously uses a set of three synthesis/design decision variables (wing span and root and tip chord lengths) for the AFS-A and another three for the PS (compressor ratio and design corrected flow rates for the compressor and turbine) as well as a set of 66 operational decision variables for the PS (compressor ratio and combustor and afterburner fuel/air ratios for each of the 22 mission segments) and another 88 for the AFS-A (sweep angle, wing span, and root and tip chord lengths for each of the 22 mission segments) to determine the optimal AAF synthesis/design and the most efficient wing configuration for each segment of the mission. It is assumed that a morphing wing is heavier than a conventional wing of the same size because of the addition of hinges, actuators, etc. A multiplication factor on conventional wing weight is used in the analysis.

In addition, the power required to actuate the morphing wing is calculated as a percentage increase in mission fuel required. Both of these 'penalties' are considered over a wide range of values in order to demonstrate the sensitivity to these effects. The optimisation metric of minimum weight of fuel burned is used to represent energy efficiency, instead of the conventional minimisation of vehicle weight.

Results for this work are presented in Fig. 2(4), showing the benefits in terms of mission fuel burned by a morphing concept compared with the



Mission segments

No.	Name
1	Warm up
2	Take off
3	Subsonic Acceleration 1
4	Subsonic Acceleration/Climb
5	Subsonic Cruise 1
6	Combat Air Patrol/Loiter
7	Subsonic Acceleration 2
8	Transonic Acceleration 1
9	Supersonic Acceleration 1
10	Supersonic Penetration
11	Combat Turn 1
12	Combat Turn 2
13	Subsonic Acceleration 3
14	Transonic Acceleration 2
15	Supersonic Acceleration 2
16	Deliver Expendables
17	Escape Dash
18	Supersonic Climb
19	Transonic Climb
20	Subsonic Cruise 2
21	Loiter
22	Landing

Figure 1. Translation of the mission described in Table 1 into the 22–mission segments used for optimising the synthesis/design of the AAF(3,4).

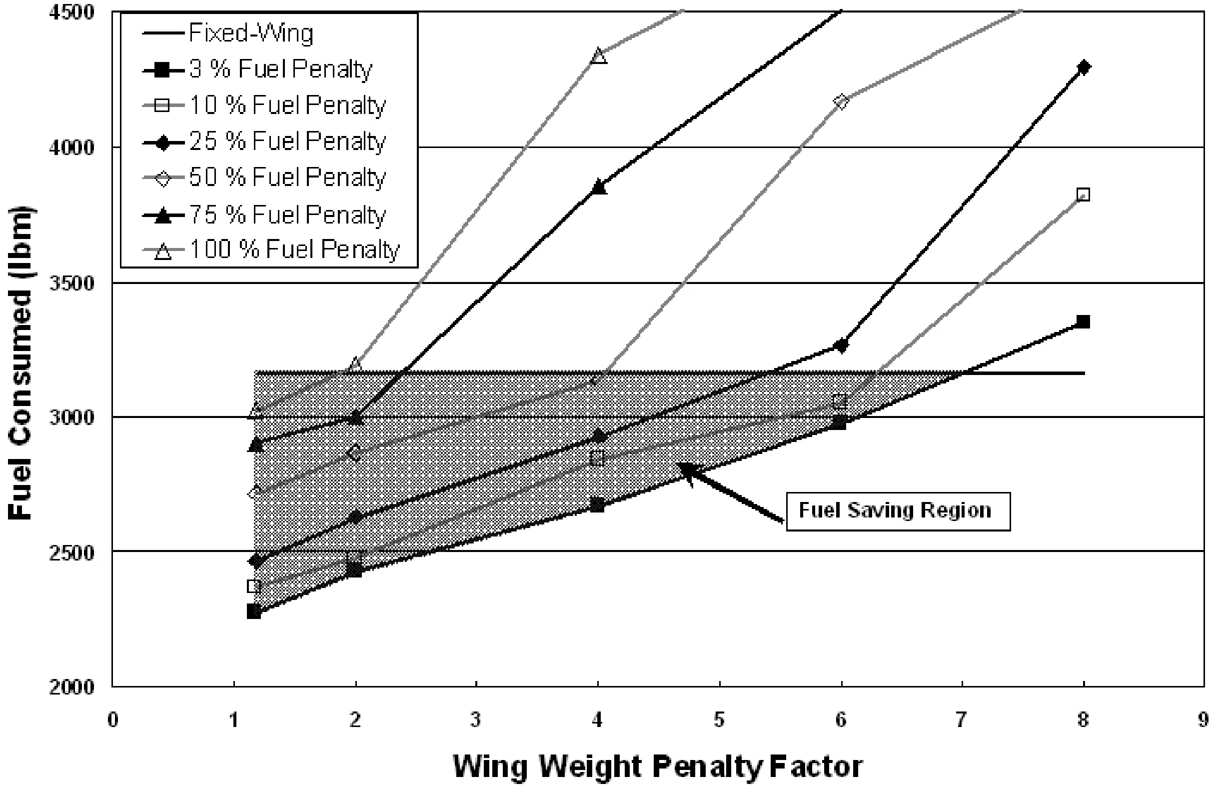


Figure 2. Optimised mission benefits of wing morphing *vs* weight and actuation penalties for a 22-segment AAF mission(4).

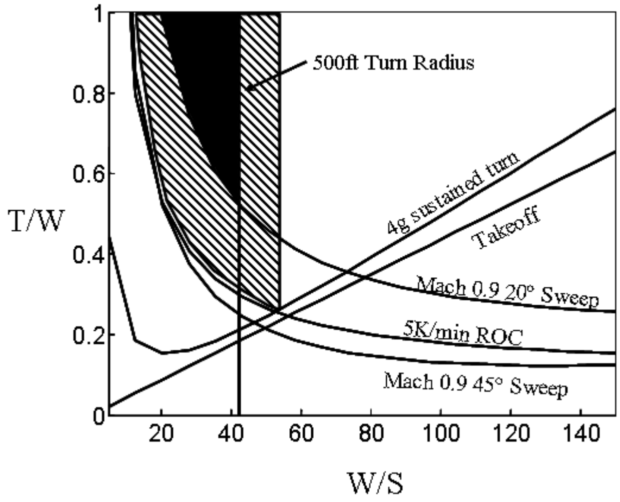


Figure 3. Effect of morphing on the synthesis/design space, thrust to weight *vs* wing loading.

similarly optimised non-morphing (fixed-wing) configuration. These results do show some boundaries. For example, if the wing weight is a factor of seven times heavier than non-morphing, there would be no benefit and similarly if the actuation penalty is much more than 100% of the baseline fuel burned. These are definitely extreme numbers, and we would expect mission benefits for practical values of these penalties. As an example, if the weight factor were about two and the actuation penalty 10%, then the mission benefit would be approximately 22% less fuel burned. This is an example of adding 'good weight' to a baseline, i.e. not the normal design paradigm. Any actual values, including reduced vehicle weight, or increased range, etc. (and also the cost effects) would obviously be specific to the mission application.

Another aspect to consider for morphing technology is the impact on the usable synthesis/design space, illustrated by the constraint diagram shown in Fig. 3(5). For a non-morphing vehicle that must meet a set of performance requirements simultaneously, the synthesis/design space is limited to the dark shaded region provided that no AFS-A degrees of freedom are considered during the synthesis/design phase of vehicle development. If, however, the vehicle wing area and sweep, for example, are allowed to change independently as would be the case if AFS-A degrees of freedom were considered during the synthesis/design phase (possible with the fixed- and morphing-wing configurations) and/or operational phase (possible with the morphing-wing configuration only), the synthesis/design space would be increased as shown by the hatched area. This is only a very simple example, and obviously the designer has more flexibility in trading installed thrust, weight, and wing parameters. Additionally, we can infer even more benefit from the new ability to be able to optimise for a far wider and more flexible range of mission requirements and constraints.

3.0 DESIGN CHALLENGES

The preceding discussion has shown the benefits of a capability to vary wing geometry more than has been available to date. The results in Fig. 2 show expected trends in mission benefits subject to the expected penalties. That analysis obviously considered the shape optimisation segment by segment, but we could also assess whether real time shape control would be more beneficial overall. The design challenge now becomes a question of how to mechanise such variable geometries with the required actuation. The aspects of our work that relate to this design challenge will be discussed below. In addition, there is always the uncertainty and risk introduced by errors in the aerodynamic model which must be considered in the design process. These errors are critical in the areas of both structural and flight control system design. The risk must be considered to be magnified when that aerodynamic model is time varying. Will traditional methodologies be sufficient? The authors suggest that the answer is: 'most likely not', i.e. new methods are needed. A new method that is being developed follows previous work(6), that considers a vehicle as a device to accomplish work and all components can be optimised to minimise energy consumption at the system level. It is envisioned to be a multidisciplinary research program that strives to understand the energy relationship between aerodynamics, structures, control, actuator power requirements, sensor integration and all other components.

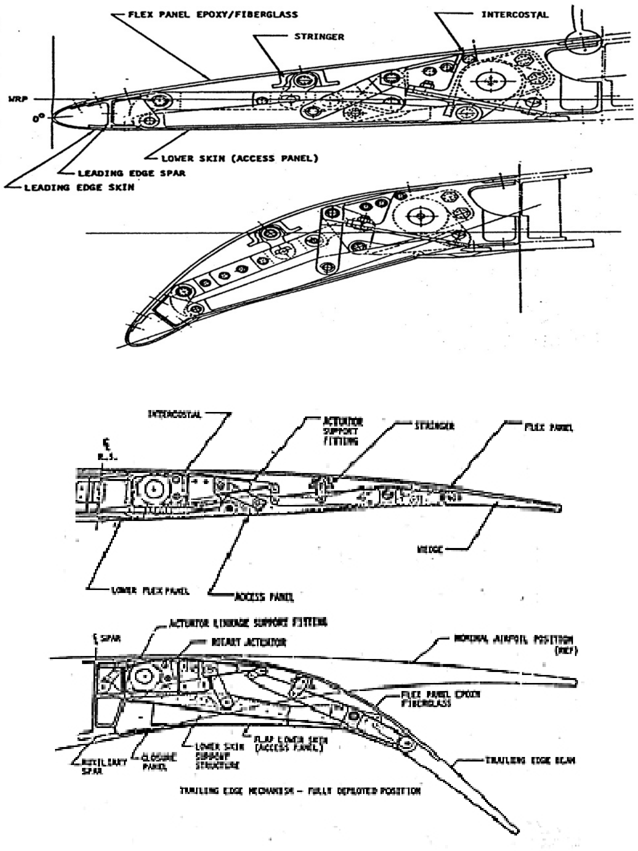


Figure 4. Mechanisation of the mission adaptive wing (MAW)(8).

3.1 Concepts of mechanisation

The preceding section discussed the benefits of changing geometry taking account of penalties, but we still need to address exactly how to produce such changes. In general terms, current flying examples of 'morphing aircraft' include flaps to vary camber and area, and wing sweep. All of these should be considered discrete structural elements moved by hydraulic or (more recently) electric actuators. Perhaps one of the best examples of a shape changing aircraft is the mission adaptive wing (MAW) development in the 1970s of the AFTI/F-111(7,8). This program showed the improvements available using internal actuators to reform the wing into various camber shapes for various root to tip lift distributions, in addition to the variable wing sweep of the basic aircraft. The MAW program is perhaps the first program to flight test a coordinated set of control surfaces. A highly unique aspect of the control surface design is that they were smoothly contoured in the chordwise direction. This concept was referred to as smooth skin variable camber because, at all shapes, the wing maintained a continuous and smooth upper surface contour. The trailing edge was divided into three discrete segments. This enabled some spanwise distribution of control surface

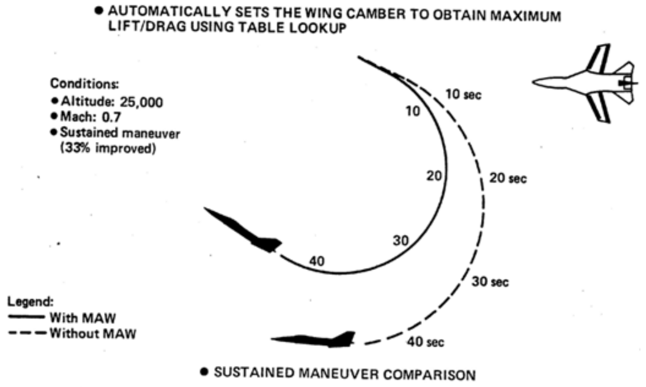


Figure 5. Example benefit of the mission adaptive wing (MAW) technology.

deflection during cruise and maneouver segments of flight. The vehicle was also configured with a single leading edge control surface that ran the entire length of each wing. The MAW development did not re-contour the box region of the wing leaving it available for fuel. The mechanisation that enabled this deformation is shown in Fig. 4, indicating the conventional mechanical linkages.

Analysis of the flight test results indicated the ability of optimal control of wing camber to increase range and maneuverability of a 7·33g, supersonic fighter by over 25% (notionally illustrated in Fig. 5).

We suggest that a new technology of structures with an embedded system of actuators is the key to further advancements. Three basic issues need to be addressed before the benefits can truly be realised. First, there must be a fundamental change in the philosophy of how structures are designed. They need to be designed from the start with desirable deformation characteristics. This will challenge traditional notions of how an air vehicle structure, such as a wing, is constructed. Second, a better understanding of how to optimise the distribution of sensors and actuators in addition to structural properties, such as mass and stiffness, needs to be developed. Third, there is a strong need to understand the scalability of these concepts (e.g., for what size are actuation concepts best suited from a systems level perspective). A fundamental hypothesis of the proposed research is that the energy-based concept will address the scalability issue since it is a basic metric common to all systems. These three topics are interrelated and must be pursued simultaneously. The challenge put forth is to achieve this integration with an approach using energy (i.e. fuel) minimisation as the optimisation metric. This requires an integration of all aspects of the vehicle on the basis of a common currency, rather than implicit assumptions that minimum weight gives the ideal answer.

Previous design experience does not include the energy absorbed into the structure, or dissipated through various means. Recent work has investigated the energy considerations of adaptive structures. The obvious driver is that these mechanisms must work effectively and efficiently under significant airloads, and also have system-level benefits. Some demonstrations have been conducted to address such issues. The integration of smart material based actuation systems has been assessed for cruise and maneuver control of aircraft(9). Mechanising a high aspect ratio wing to optimise loiter(10). Concepts for shape control have also been investigated for gas turbine engine inlets for supersonic aircraft, applications for a large-scale marine propulsion system and for a hydrodynamic maneuvering system(11).

Several recent efforts have looked at smaller scale deformations for various system concepts. However, more challenging problems are in the large-scale shape changes that will enable the types of deformation described above. This is going to require rigid body motions coupled with small-scale elastic deformations and wrapped in a skin that allows this deformation. Hence, solutions to wing construction other than the box beam configuration must be investigated since the energy requirement of deforming such a structure, even a little bit, has extremely high power requirements. The treatment of 'structure' as an energy subsystem requires a paradigm change. Initial work has been accomplished in this area, in terms of defining all the work and energy aspects for efficient deformations of adaptive structures(12,13).

3.2 Non-linear issues

For even the simplified example shown above, it should be obvious that linear design and analysis methods need to be considered subject to significant errors. As one extreme, any required loiter capability would tend to require higher aspect ratios. Assuming that the configuration would have some amount of flexibility, non-linear analysis and design has been shown to be an absolute requirement by prior work at AFRL(14). What may not be as obvious, however, is the indication that even rigid-body effects can be non-linear. Such effects could also be time dependent as we consider faster rates of change for the different geometries. As we progress towards capabilities for greater and greater changes in the geometrical configurations, there is the potential for some to be essentially linear and others definitely non-linear. We suggest, therefore, that such considerations should not be ignored since the risk of discovering a significant effect late in the design process is unacceptable. It is obviously even worse to find such problems in flight(15). There has also been consideration of the interactions of the structure and the control system(16), with discussion of topics such as maneuver load control, deformation control, elastic mode control and flutter suppression. There is discussion of the progress from 'repairing problems' to the use of active control technology in the structural design process – leading to the next section.

3.3 Flight control issues

An issue which must be raised is the question of the most appropriate approach to flight control system design for a morphing configuration. In preceding sections, the possibilities of adaptive structures for near real-time performance optimisation were discussed. One potential configuration is shown in Fig. 6, where the in-board wing section folds against the fuselage with the out-board section staying parallel with the original position (when not loaded). The wing thus has less area, i.e. suitable for a higher speed mission segment. Analysis of the modal characteristics versus fold angle (i.e. angle between the inboard wing section and the horizontal plane) is also shown in Fig. 6(17). Here, 1B represents the first bending mode, 2B the second bending mode, FBT designates fuselage bending driving wing torsion, FBB designates fuselage bending driving wind bending, Tin is the torsion of the inner wing section and Tout represents torsion of the outer wing section. This figure illustrates that the modes have frequencies less than approximately 30Hz, which would allow the flight control to be designed with filters in the command paths to mitigate coupling. A major exception, however, would be the inboard wing torsional mode, which has significant non-linear variation with deflection angle of the wing fold. This would require detailed attention during the flight control design process.

Traditional design has been based on a predicted aerodynamic model (typically from analysis and wind tunnel results). The flight control gains were then based on this model, and a re-design would be done if flight experiments indicated problems. The 'latest technology'(18,19) includes a neural network to identify the actual aerodynamic model in flight and then the flight control gains, filters, etc., are adjusted continually to match this 'real data'. When we address the previously discussed real-time morphing capability, then it must be obvious that a neural net may be 'catching up' with the continuously changing system model. In addition, the actuation characteristics are probably going to be time dependent, as well. A question for this technology may be: 'what amount of time delay is acceptable for the identification process?'. For piloted aircraft a maximum equivalent system time delay of 100msec was a requirement(20). For unmanned vehicles this parameter is not easy to transfer, so a different approach to address the time delay problem is needed. The issue is to assess if there will be a bandwidth of the rate of change in the aero model that becomes too high and a problem to

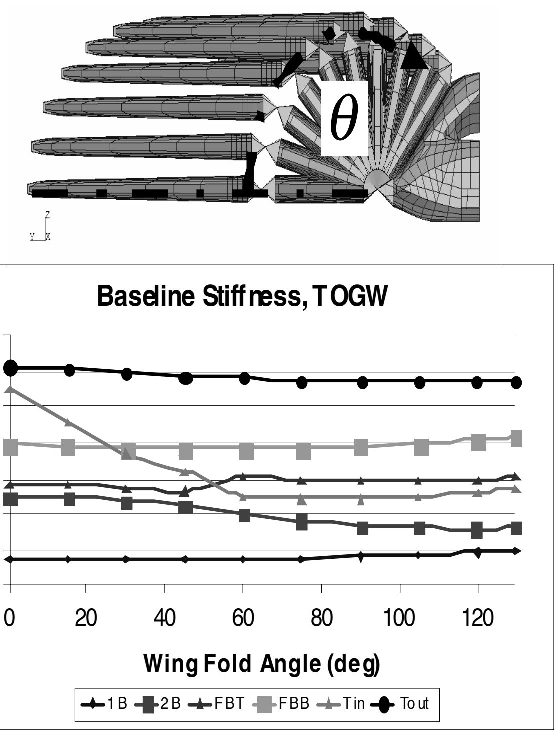


Figure 6. Estimated structural characteristics of the folding wing.

address. One approach could be the 'old technology' of explicit model following that has been used for in-flight simulation for many years. Here a 'required model' is programmed in a computer, the flight control system then zeroes any differences between the actual vehicle responses and what the response of the ideal required model would be. It needs to be assessed if the morphing vehicle can be controlled to respond in accordance with a pre-defined definition of an ideal model.

4.0 INTEGRATION ISSUES

It is suggested that any morphing aircraft configuration will require a design process that fully integrates the structure, aerodynamics and the control system. We previously discussed development of a system-level integration methodology based on the complete integration of all the aspects of work required to do the mission using the energy available from the fuel. It will consider all the different energy forms, stored, generated, wasted, etc.

Finally, we consider that a practical design would have to form an integrated approach to failure cases and required redundancies. The concept of distributed sensing and actuation could address this aspect if considered correctly through the whole design process. One approach common in FCS design would be to construct the matrix of probability of occurrence of a failure vs the effect of that failure.

5.0 CONCLUSIONS

It is concluded that there are definite benefits from the consideration of fully adaptive structure, provided that the mission is not dominated by one aspect such as cruise. We also suggest that conventional design methods are deficient. In this paper we have discussed potential approaches for mechanisation to give system-level efficiency. We have suggested the need for non-linear design methods. Traditional aspects of adaptive structure, such as flap extension and deflection or changes in wing sweep, take place slowly. The question needs to be addressed as to whether the required changes will need to occur fast enough to impact the flight control system. It may be that an 'old technology' will be more applicable and should be assessed in future research. That would be consistent with our 're-invention and extension' of the adaptive structures that were used by the Wright brothers and have been continually developed ever since.

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