43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Con
22-25 April 2002, Denver, Colorado

AIAA 2002-1

AIAA-2002-1631

EVALUATING THE IMPACT OF MORPHING TECHNOLOGIES ON AIRCRAFT PERFORMANCE

Jason Bowman
Jason.Bowman@wpafb.af.mil
Multifunction Aerospace Structures Team
Air Force Research Labs
WPAFB, OH

Major Brian Sanders
Brian.Sanders@wpafb.af.mil
Multifunction Aerospace Structures Team
Air Force Research Labs
WPAFB, OH

Dr. Terrence Weisshaar
weisshaa@ecn.purdue.edu
School of Aeronautics & Astronautics
Purdue University
West Lafayette, IN

Abstract

A mathematical evaluation of some bird morphing mechanisms is presented to demonstrate potential benefits of morphing principles on larger air vehicles. The ability to control wing shape in planform and profile is especially important. Some basic relationships are presented for determining the drag characteristics when morphing is employed. The effects of morphing on vehicle kinematics is demonstrated for a turn radius requirement. At a system level, the effects of variable lift-to-drag ratio and specific fuel consumption on vehicle weight are examined for cruising flight. Any morphing technology that maps into lift-to-drag ratio or specific fuel consumption can then be evaluated. An example mission is presented to demonstrate how morphing can be implemented in constraint and sizing analyses, which are at the core of the aircraft conceptual design process.

Nomenclature

a	speed of sound
AR	aspect ratio, b^2/S_{wing}
b	wing span
β	weight fraction
c_{HT}, c_{VT}	horizontal, vertical tail volume coefficients
C_L, C_D	drag and lift coefficients
C_{D_p}	parasitic drag coefficient
C_{f_e}	equivalent skin friction coefficient
C_{L_0}	lift coefficient for minimum drag
e	Oswald's span efficiency
ε	thrust gimbal angle
g	acceleration due to gravity
γ	flight path angle
Γ	ratio of area to reference area, S/S_0
ISR	intelligence, surveillance, reconnaissance
k	induced drag factor, $1/(\pi \mathrm{AR} e)$
kts	knots
L/D	lift-to-drag ratio
M	mach number
n	load factor
NM	nautical mile
q	dynamic pressure, $(1/2)\rho V^2$
R	range
ρ	air density
S	area
SFC	specific fuel consumption
T/W	thrust-to-weight ratio
V	speed
W	weight
W/S	wing loading
X	wetted area ratio, S_{wet}/S_{wing}

Introduction

There is increasing pressure, both political and economic, for aircraft that can do it all. One notable attempt was the F-4 Phantom designed for both the fighter and attack roles. Later generation aircraft such as the F-18 Hornet with improved structures and aerodynamics could even act as their own escort. Yet the description "jack-of-all-trades, master of none" still rings true today. Even for aircraft designed primarily for one mission, improvements in performance have tended to be evolutionary over the last few decades rather than revolutionary.

The inability for a given aircraft to perform multiple missions well is due to shape, at least if aerodynamic performance is the consideration. For a given task, there is usually an ideal vehicle configuration. A simple example is flaps, which are retracted during cruise and deployed for takeoff and landing. Flaps allow the wing to be sized for cruise where most of the fuel is burned but still be able to takeoff and land in reasonable distances.

The problem until recently was how to modify the vehicle shape the amount necessary to achieve revolutionary performance gains. The Mission Adaptive Wing tested on the swing wing F-111 in the 1980's used traditional actuators and structural configurations resulting in weights gains that were impractical.

However, progress in material and actuator development in the past decade and recognition that new structural configurations are required to enable radical shape change has helped form the concept of morphing. Morphing is a short form of the word metamorphose, which means "to change the form or nature of".[1]

If "to change the nature of" is considered, a more general definition of morphing is "a set of *technologies* that increase a vehicle's *performance* by manipulating certain *characteristics* to better match the vehicle state to the *environment* and task at hand". Technologies may include new actuators, effectors, and smart materials. Performance is measured by what the customer deems to be important: range, weight, cost, maneuverability, RCS, payload, or perhaps a combination of these by using Quality Function Deployment (QFD). Characteristics may include geometry and mechanical and electromagnetic material properties. Environment can mean the atmosphere and electromagnetic spectrum for example.

Older technologies such as retractable landing gear and flaps would be considered morphing technologies using this definition as would signature modification. However, morphing carries the connotation of radical shape change or shape changes only possible with near-term or futuristic technologies. Therefore, when morphing is used in this document it will only refer to shapes changes, not general changes in state, that are radical.

Currently, morphing is at the technology push stage of development. There are several notions of the benefits of morphing, but to date morphing has yet to be considered as a requirement or at least a consideration in a requirements generation process. As the technology is pushed up to users and customers in a way that the benefits of the technology is very clear to them, the users will begin to reach down and generate requirements that will make use of the technology.

One way to begin to demonstrate the benefits to users is to treat morphing as an independent variable. That is, if morphing were possible, what would be the benefits? Obviously, every possibility can not be investigated in this paper or even ten papers. However, some guiding principles and examples will be presented.

Motivation

Birds are a natural example of morphing at work. It would be remiss of scientists and engineers not to look towards the birds for motivation. However, birds only occupy a small region of the total flight envelope that spans from insects to jumbo jets. It would also be remiss then to assume bird morphology would always apply to larger air vehicles.

That being said, one of the intriguing aspects of morphing mechanisms on birds is that they are highly integrated, that is they are multifunctional. For instance, a bird wing is designed to lift and propel while providing the necessary additional forces and moments to trim (balance). A bird wing also changes its basic shape, both in the planform and profile view, depending on the flight condition while still performing these various functions. Examples of the range of configurations possible by birds are shown in Figure 1.

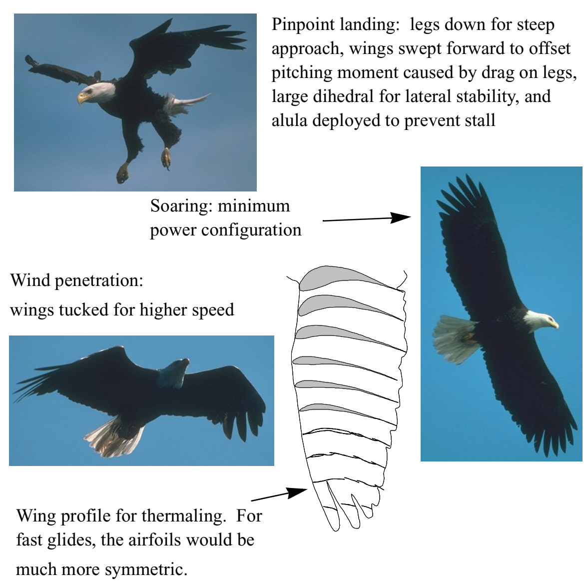

Figure 1: Bald Eagle In Various Configurations

One of the key features seen in Figure 1 is the ability to greatly change the wing planform shape. The lay explanation is that birds spread their wings to fly slow and tuck them to fly fast. While this is true, so much more can be learned by studying the relevant performance equations.

This particular observation is easy to see from the definition of the lift coefficient:

$$C_L \equiv \frac{W}{\frac{1}{2}\rho V^2 S} \tag{1}$$

Solving for the speed gives $V = \sqrt{\frac{2W}{\rho S C_L}}$. If the lift coefficient is held constant as the wing is tucked, then a decrease in wing area S must result in a higher flight speed if the forces on the bird are to remain in equilibrium. In fact, the wing loading W/S is the primary controller for flight speed with or without propulsion. The same argument can be made using the drag coefficient, but the analysis is more difficult since the drag polar (relationship between C_D and C_L) can change significantly with changes in shape.

One reason to tuck the wings for speed is to dive quickly. In a dive, the lift is low and the drag is mostly friction drag. Therefore, any reduction in surface area will allow a higher terminal speed.

Another reason to tuck the wings for speed is improved wind penetration. In this situation, an important question might be what is the optimal wing area to minimize sink speed or glide angle? To determine this, the drag characteristics are needed. Assuming

$$C_D = C_{D_p} + k(C_L - C_{L_0})^2 \tag{2}$$

and using the definition of lift and drag coefficient, the best wing area for both cases for a given forward speed is given by

$$S^2 = \frac{kW^2}{q[q(C_{D_p} + kC_{L_0}^2) - 2kWC_{L_0}]} \tag{3}$$

If the bird is symmetric in profile, then $C_{L_0} = 0$ and

$$S = \frac{W}{q}\frac{1}{C_L^*} \tag{4}$$

where $C_L^* = \sqrt{\frac{C_{D_p}}{k}}$, which is the lift coefficient for best lift-to-drag ratio.

These results assume that k and C_{D_p} stay constant as the wing changes, which is not accurate. How they change, however, will be discussed shortly. As a first order analysis, though, it shows that when flying fast (high q), the wing area should be small, and when flying slow the wing area should be large. The optimal wing area calculated this way is consistent with equalizing the two types of drag, which is the condition for maximum lift-to-drag ratio.

If the problem had been to find the minimum sink speed for a given area, the lift coefficient would have been for best $\frac{C_L^{3/2}}{C_D}$, which is $C_L = \sqrt{3\frac{C_{D_p}}{k}}$. It is not coincidence that the types of geometry that produce large values of $\frac{C_L^{3/2}}{C_D}$ are the highly cambered airfoils shown in Figure 1 (plot this ratio for increasing values of C_{L_0}, representing increasing camber, to see this).

The wing profile shown in Figure 1 is also an interesting morphing mechanism. A large amount of camber is useful for decreasing the stall speed by increasing the maximum lift coefficient. This allows slower and safer landing speeds. A large amount of camber also produces less drag at slower speeds where the lift coefficient is high. The reason is that the zero lift drag coefficient, to be discussed in the drag polar section, increases with camber. With increasing camber, the minimum drag point shifts to the higher lift coefficients (slower flight speeds) where the bird is flying. The same argument holds true for fast flight speeds, except the lift coefficient is low, so camber has to be low to shift the minimum drag point to the lower lift coefficients.

In an approach to landing, as shown in Figure 1, birds will adjust the position of their legs from fully down to fully retracted. Legs in the down position act as bluff bodies greatly increasing the drag. Since the glide angle is given by $\gamma = -\frac{1}{L/D}$, any increase in drag for the same lift steepens the approach, and any a decrease in drag shallows the approach.

Finally, birds can vary the wing dihedral angle. During the approach to landing shown in Figure 1, the wing dihedral is large for increased roll stability in such a steep descent. However, this causes the Dutch roll mode to be excessive. During extended gliding, this may be unacceptable in terms of both flying qualities and energy expenditure. One exception is flying in thermals. Perhaps good roll stability is required to remain inside the rising, small radius columns of air.

Identification of Morphing Mechanisms

Throughout this paper, it will be necessary to break down a requirement or expression to identify morphing mechanisms. Structured design methods can be used to determine which vehicle attributes should be modified to achieve the desired level of performance.

The process starts with a figure-of-merit. The figure-of-merit might be a QFD matrix, representing the collective performance of the system, or an equation for a narrow measure of performance such as turn rate, which might be a part of the QFD matrix.

The process to identify morphing mechanisms is to take the figure-of-merit, what the customer deems to be important, and apply a decomposition process to it. Although more complicated when using the QFD matrix, a single measure of performance is adequate to demonstrate the process. The key is to look for terms in the figure-of-merit or that can be affected by technology.

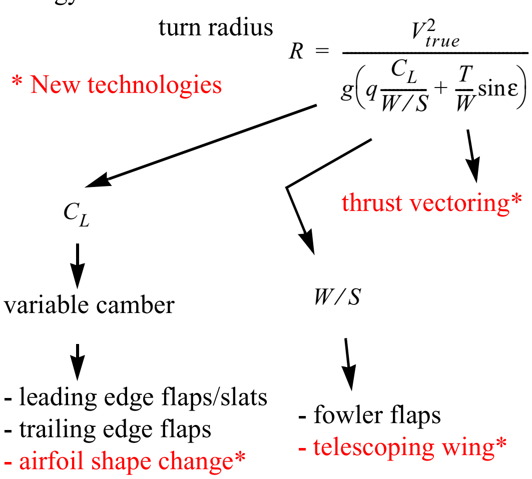

Figure 2: Several Levels of Functional Decomposition Applied to a Turn Radius Requirement

As can be seen in Figure 2, the turn radius expression contains three technology parameters: wing area, lift coefficient, and the thrust gimbal angle. At this point, the physical mechanisms appear such as flaps, airfoil shape change, and telescoping wings. One could take the decomposition even further. To accomplish an airfoil shape change, one might need to consider smart materials and new types of actuation.

Drag Polars

The purpose of this section is to demonstrate how the drag polar changes as a result of morphing. Expressions are developed that allow the technology parameters in the drag polar for a morphed configuration to be expressed in terms of a baseline. This would be useful in the early conceptual stage of design.

Equation 2 is broken down into two basic types of drag — parasitic (friction) drag and drag induced by lift. Induced drag is a 3D phenomenon, but even in 2D the parasitic drag shows a variation with lift. For convenience, the parasitic variation with lift is included with the induced drag. This allows the parasitic drag to be estimated using simple estimators such as or historical data or flat plates with suitable corrections.

Using historical data allows the parasitic drag coefficient to be expressed as

$$C_{D_p} = C_{f_e}\frac{S_{wet}}{S_{wing}} \tag{5}$$

where C_{f_e} is the equivalent skin friction coefficient based on historical data (similar aircraft), S_{wet} is the total area exposed to the airstream, and S_{wing} is the planform area of the wing.

If the configuration remains similar throughout the range of morphing, the only expression needed is one for wetted area ratio. If it is assumed that changes in the wing area is the primary morphing mechanism, the wetted area ratio X can be computed in terms of the baseline as

$$X = 2m\left(1 - \frac{1}{\Gamma}\right) + \frac{X_0}{\Gamma} \tag{6}$$

where $\Gamma \equiv \frac{S}{S_0}$ and m accounts for the extra area due to airfoil curvature and is typically 1.03 - 1.05. Typical values of wetted area ratio can be found in many design texts.[2]

If stability is to be considered as the wing area changes, one way to account for this is to use tail volume coefficients, which are a convenient way to estimate tail sizes in the conceptual phase of design. The vertical tail size is estimated as

$$S_{VT} = c_{VT}\frac{b_{wing}}{L_{VT}}\Gamma S_{wing,\,0} \tag{7}$$

and the horizontal tail size is estimated as

$$S_{HT} = c_{HT}\frac{\bar{c}_{wing}}{L_{HT}}\Gamma S_{wing,\,0} \qquad (8)$$

The tail volume coefficients c_{VT} and c_{HT} for various aircraft types can be found in standard tables.[2] These expressions can then be inserted into the wetted area calculation as before, but if the span- or chord-to-moment arm ratios change, this must be accounted for in terms of the original ratio as was done with wing area.

If changes are restricted to wing area as before, an expression can be developed if the baseline and wing C_{D_p} are known.

$$C_{D_p} = C_{D_{p,\,wing}}\left(1 - \frac{1}{\Gamma}\right) + \frac{C_{D_{p,\,0}}}{\Gamma} \qquad (9)$$

Note that when $\Gamma = 1$, the original C_{D_p} is recovered, and when $\Gamma \to \infty$, i.e. the wing is large compared to the rest of the components, $C_{D_p} = C_{D_{p,\,wing}}$ as it should. This might be useful if the drag is known *a priori*. For typical conceptual design, though, it is simpler and more accurate to perform a drag buildup for each configuration required given that the estimation will probably be done in a computer and the computations are very fast.

The next parameter in the drag polar is the induced drag factor *k*, which can be expressed as $\frac{1}{\pi \mathrm{AR} e}$, where AR is the wing aspect ratio, and *e*, Oswald's span efficiency, is a complicated function of C_{D_p} (recall the parasitic variation with C_L is included) and wing planform, including AR, wing sweep, and the wing chord, twist, and camber distributions. However, the contribution of C_{D_p}, sweep, camber, twist, and chord distribution is relatively minor compared to the effect of aspect ratio.[3] Therefore, initially the value of *e* can be fixed unless of course suitable estimators are available.[4]

Finally, the minimum drag lift coefficient C_{L_0} is dominated by wing camber and can greatly influence the maximum lift-to-drag ratio (C_{L_0} allows a higher lift coefficient for the same drag coefficient). The typical assumption $C_{L_0} = 0$ is not accurate for long range or endurance flights where the fuel fraction is sensitive to lift-to-drag ratio. However, practical estimation of C_{L_0} often requires computational methods (to account for twist, camber, and chord distributions) and even wind tunnel testing in some circumstances (fuselages with large aft upsweeps will have minimum drag at a positive angle-of-attack). Typical values, though, range between 0.0 and 0.2. High flyers with large camber may have $C_{L_0} > 0.3$.

Morphing Kinematics

If the scope of morphing is restrict to shape changes, the increase in performance is due to modification of the vehicle aerodynamics, specifically the forces and moments. Knowing the forces and moments allows the vehicle kinematics to be described. Kinematics is the relationship between force, acceleration, velocity, and position, but for aircraft can also include weight-independent calculations such as takeoff and landing distances and turn rate. Figure 3 illustrates the forces and moments in the pitch plane. Morphing can affect both the direction and magnitude of the forces and pitching moment.

The lift and drag directions are always perpendicular and parallel to the velocity vector, respectively, and can only be indirectly affected through morphing. The direction of weight is always vertically down and can not be affected through morphing. The direction of the thrust can be varied with thrust vectoring devices. Therefore thrust is the only force whose direction can be directly changed by morphing.

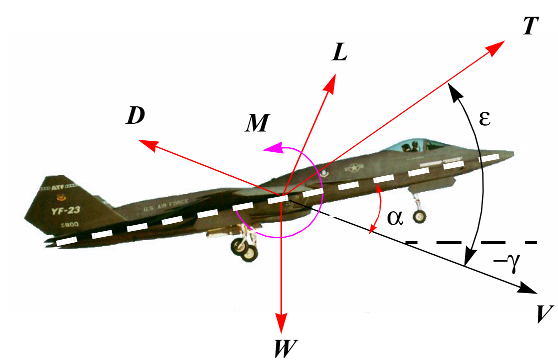

Figure 3: Typical Free-Body Diagram

With the exception of weight (drag affects the fuel required which affects the sized weight), the magnitudes of the forces and pitching moment are directly affected by morphing. Wing shape (camber, twist, chord, planform, etc.) will affect the lift, drag, and pitching moment magnitudes while engine inlet, compressor, combustor, turbine, and nozzle geometry will affect the throttle setting for a given amount of thrust and the maximum thrust available.

Since lift can be increased for a given speed or maintained with decreasing airspeed with a change in angle-of-attack, the actual purpose of morphing to modify lift is to achieve a given lift force at a particular angle-of-attack. Also, since $L = W$ in steady, level flight and fuel is consumed or payload expended during the mission, lift must decrease accordingly. This is an elusion to the cruise-climb problem current air traffic control regulations require constant altitude — constant airspeed flight resulting in a non-optimal aerodynamic state.

When the thrust is aligned with the velocity vector, which is the usual assumption, it is natural to compute the lift coefficient as $C_L = \frac{n(W/S)\cos\gamma}{q}$. For small flight path angles, the flight speed can be expressed as $V = \sqrt{\frac{2nW}{\rho S C_L}}$. What most fail to consider is that SC_L is the key quantity and not C_L. Determining the correct mix of the two or if there is a benefit to changing the wing area requires constraint and weight studies, which are discussed later.

Since thrust can be vectored to help support the weight of the vehicle, it should be accounted for. If the total "lift" force on the vehicle is defined as $L + T\sin\varepsilon$, then

$$C_{L,\,TOTAL} = n^*\frac{W/S}{q}$$

$$or \tag{10}$$

$$C_{L,\,total} = C_{L,\,wing} + \frac{(T/W)(W/S)\sin\varepsilon}{q}$$

where $n^* = n + (T/W)\sin\varepsilon$ (the g-force felt by the "pilot") and $n = L/W$. The load factor n accounts for conditions other than straight and level flight allowing designers to use the wing loading W/S as a primary design parameter. Equation 10 indicates that thrust vectoring is potentially most effective (the thrust term has a dependence on q) at low speeds (low q) where the wing is nearing its stall angle-of-attack.

To answer this definitively, consider a turn radius requirement. If the usual constant-altitude constraint is removed allowing a 90º banked turn, the turn radius R can be expressed as

$$R = \frac{V_{true}^2}{g\left(q\frac{C_L}{W/S} + \frac{T}{W}\sin\varepsilon\right)} \tag{11}$$

Contours of equation 11 are plotted in Figure 4 for $C_L = 1.5$, $T/W = 1$, and $\varepsilon = 90°$. Overlaid are the 3-, 6-, and 9g load factor contours for reference.

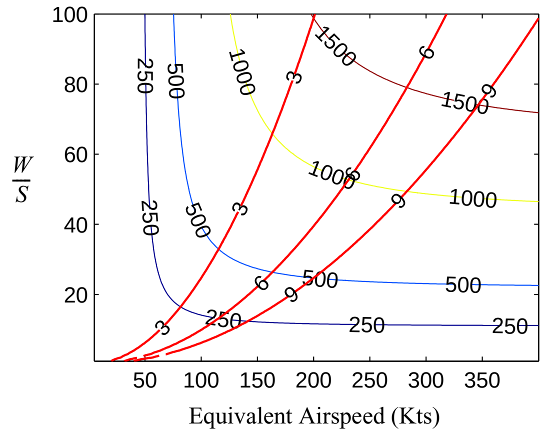

Figure 4: Turn Radius (ft) Contours with Thrust Vectoring

As suggested before, thrust vectoring is most effective at low speeds and least effective at high speeds. Other plots based on equation 11 can be constructed to demonstrate the effect of C_L and W/S, which then can be mapped to morphing technologies as illustrated in Figure 2.

The Cruise-Climb Problem

The cruise-climb problem has been a topic of concern ever since air traffic control regulations forced aircraft to fly constant altitude — constant speed profiles. The problem is that as fuel is burned, the lift coefficient must decrease if this profile is flown. Since there is only one optimal lift coefficient for cruise, the lift-to-drag ratio can only be optimal at one point during the cruise. At every other point the aircraft is not as fuel efficient.

The problem is somewhat alleviated by allowing aircraft to climb in 4,000 ft increments, which requires an approximate 10% decrease in weight. The decrease in air density increases the lift coefficient again towards its optimal value. This profile is called a step-climb.

Once in a while there is anecdotal discussion on changing wing area to accomplish the same thing. Recall the definition of lift coefficient in equation 1. A decrease in density or wing area both increase the lift coefficient.

However, what is usually ignored is that the drag characteristics change if the wing area changes, which changes the jet optimal lift coefficient $C_L = \sqrt{\frac{1}{3}\frac{C_{D_p}}{k}}$. Specifically, a decrease in wing area increases C_{D_p}, and the induced drag factor k will increase or decrease if the span or chord is reduced, respectively.

For a flying wing with a wetted area ratio near 2.5 and where C_{D_p} is almost entirely from the wing friction drag, the optimal lift coefficient will not change as much if at all, so there is benefit in reducing wing area for flying wings. It is not so clear what happens on configurations with high wetted area ratios such as a Boeing 747.

To find out, the wetted area of a 747-400 was broken down into components and tail areas were adjusted in proportion to the wing area to ensure an accurate calculation of wetted area ratio as the wing changed area. This wetted area ratio was then used to calculate a wetted aspect ratio and ultimately the maximum lift-to-drag ratio using historical data.[2] The results are shown in Figure 5 for three cases: span changes, chord changes, and span and chord changes to maintain aspect ratio.

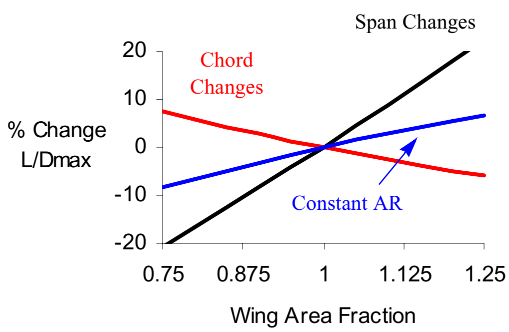

Figure 5: Changes in Maximum L/D Due to Changes in Wing Area

One interesting trend is that the wing area should be increased not decreased for increased lift-to-drag ratio. This occurs because as the wing grows in size relative to the rest of the aircraft, the aircraft is more like a flying wing. There must be a reason why the wing was not made bigger in the first place, and this illustrates the depth of complexity of this seemingly simple problem. If this result were to be believed, the wing should be smaller or bigger. The worst lift-to-drag ratio occurs with the wing as is.

Part of the problem is that the flight lift-to-drag ratio was not calculated, just the maximum. A short list of some of the other issues would include trouble fitting into existing gates for larger spans, flutter considerations, and structural weight. Perhaps the birds are doing it right after all. As previously discussed, a change wing area can be used to fly closer to the optimal condition across a wide speed range.

Changing wing area as weight changes might be a wash for the cruise-climb problem, but more detailed analysis is required for a definitive answer. Furthermore, as free flight is implemented and aircraft become increasingly responsible for collision avoidance, the constant altitude restriction will be removed making this problem irrelevant.

Effects of Lift-to-Drag on TOGW

One of the dangers of a technology push is that sometimes performance claims are made that do not address the effect on the system. One example would be a statement that a particular morphing technology might increase the lift-to-drag ratio 10%. While this seems like a significant increase, what if the weight savings were only 1%? This could easily be the case.

Using Takeoff Gross Weight (TOGW) as a figure-of-merit, the effect of changes in lift-to-drag ratio, L/D, and specific fuel consumption, SFC, for cruising flight will be demonstrated. While a direct relationship between TOGW and morphing is not shown, the system level performance of any technology can be mapped through this relationship.

Takeoff Gross Weight, W_{TO}, can be estimated as

$$W_{TO} = \frac{b + W_{payload}}{\beta - m} \tag{12}$$

The constants m and b are the slope and y-intercept, respectively, when the empty weight historical estimate

$$W_E = AW_{TO}^{C+1} \tag{13}$$

is linearized.[2] The constants A and C are based on a particular aircraft class. Note that the empty weight is fairly linear with TOGW but the empty weight fraction is not. The weight fraction β is the product of individual mission leg weight fractions.[2]

To see the effect of changes in L/D and SFC, the derivative of equation 12 can be taken. But it is more instructive to compute the logarithmic derivative. Putting the derivative in this form allows one to immediately estimate the percent change in TOGW with respect to a percent change in L/D (or SFC). Using the jet Breguet Range equation, $\frac{W_{i+1}}{W_i} = \exp{-\frac{R \bullet SFC}{aML/D}}$, the logarithmic derivative for TOGW with respect to L/D and SFC is

$$\frac{\partial W_{TO}}{W_{TO}} \frac{L/D}{\partial L/D} = \frac{\partial W_{TO}}{W_{TO}} \frac{SFC}{\partial SFC} = \left(\frac{R \bullet SFC}{aML/D}\right) \frac{\beta}{\beta - m} \quad (14)$$

In plain english, equation 14 states that the change in TOGW with L/D or SFC is less when the range is small, L/D is high, or SFC is low. It also says that when the empty weight is sensitive to the takeoff weight (high *m*), L/D and SFC have a larger impact on TOGW. Figure 6 shows typical empty weight—takeoff weight and takeoff weight—L/D (or SFC) sensitivities.

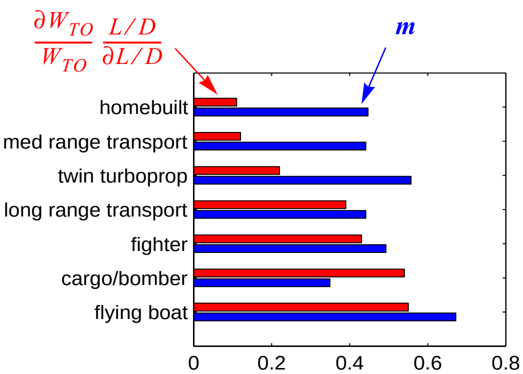

Figure 6: Empty and Takeoff Gross Weight Sensitivities of Typical Aircraft

Although the military cargo aircraft type has the lowest sensitivity of empty weight with respect to TOGW, a long range requirement makes them particularly sensitive to changes in L/D and SFC. A twin turboprop has a relatively high sensitivity of empty weight with respect to TOGW, but when used as a short range commuter aircraft, the sensitivity of TOGW with L/D and SFC is relatively low.

The sensitivity of TOGW with respect to L/D and SFC is shown in more detail for a jet transport in Figure 7 for various ranges and SFCs. The speed-of-sound, *a*, is 968ft/s at 36,000ft, and *ML/D* was assumed to be 15.

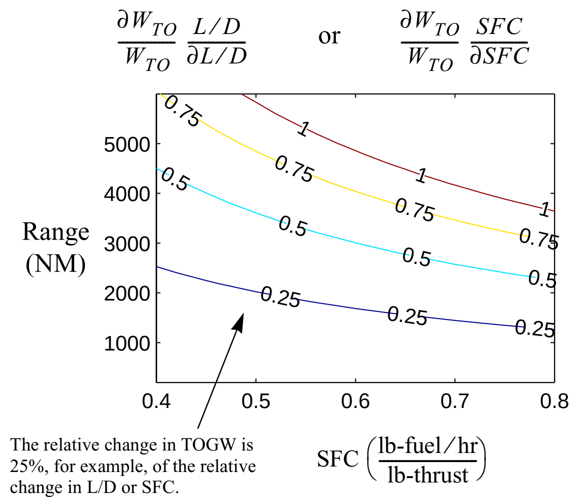

Figure 7: Contours of Relative Change in Takeoff Weight of a Jet Transport With Respect To L/D and SFC

Morphing in a System Level Trade Study

Up to this point, the discussion has primarily focused on the effects of morphing technologies on the lift-to-drag ratio and ultimately TOGW. The empty weight expression used to construct Figure 7 was only a function of TOGW, though.

Once details about the design begin to emerge, more accurate expressions for empty weight can be used. These expressions are typically functions of TOGW, aspect ratio, thrust-to-weight ratio, wing loading, and maximum Mach number as expressed in equation 15.[2]

$$W_E = aW_{TO} + bW_{TO}^{C1+1} \mathrm{AR}^{C2} \left(\frac{T}{W}\right)^{C3} \left(\frac{W}{S}\right)^{C4} M_{max}^{C5} \quad (15)$$

As before, the constants depend on the aircraft class. Note that equation 15 also represents a technology barrier. The empty weight can never be less than that given by equation 15, but it can always be larger.

The problem is how to estimate the weight for a morphing aircraft. After all, a morphing aircraft is many different types of aircraft. It does not fit any one type. But this is exactly how to estimate the weight. For each configuration, equation 15 gives the minimum empty weight that technology can achieve. In the sizing analysis, the empty weight of the morphing aircraft is simply the maximum of the empty weights for each configuration. For one configuration, there is just enough empty weight to be technologically feasible.

The other, less critical configurations just carry extra empty weight.

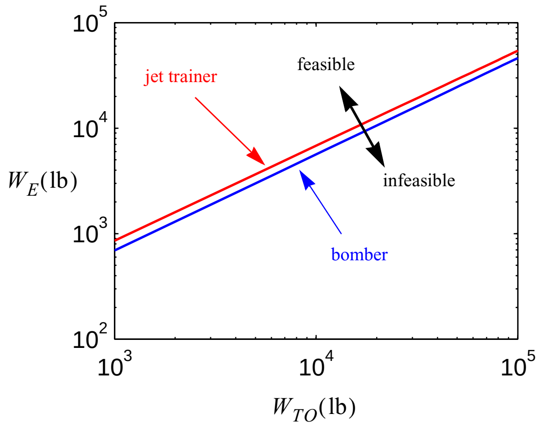

Figure 8: Variation of Empty Weight with Takeoff Weight for Two Morphing Configurations

While the maximum Mach number is usually specified by the customer, thrust-to-weight, aspect ratio, and wing loading are not. They are selected by the design engineers using trade studies. One such study is the constraint diagram, which shows the relationship between minimum required thrust-to-weight ratio for a given wing loading. Aspect ratio is automatically accounted for in the constraint diagram through the drag polar.

To demonstrate how the constraint diagram is used, consider an example ISR-Attack (ISR: intelligence, surveillance, reconnaissance) mission. One of the general requirements is to fly from point to point quickly. Assume this to mean Mach 0.9 at 30,000 ft. If flying in mountainous terrain during the attack, turn radius and sustained turn requirements are needed. Assume these requirements are 500ft-700ft and 4g's at 200 knots, respectively, with both at 15,000 ft. Finally, takeoff and rate-of-climb (for rapid egress after the attack) requirements are needed. Let these be 3,000 ft at sea-level and 5,000 ft/min at 15,000 ft at Mach 0.75, respectively.

These requirements are shown in T/W-W/S space (constraint diagram) in Figure 9. To understand the constraint diagram, feasible regions are above each line. For the vertical lines, the feasible region is to the left. Typically, TOGW is minimized when the T/W is lowest and W/S the highest, i.e. the furthest down and to the right on the constraint diagram.

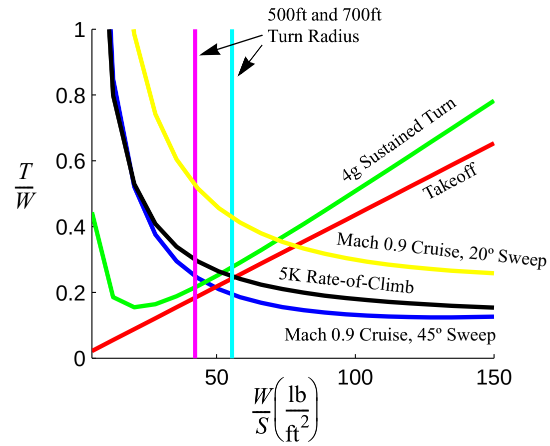

Figure 9: Constraint Diagram for an ISR-Attack Mission

It was assumed that a flight lift coefficient of 2.3 could be achieved through various means (morphing technologies and flow control perhaps) for the turn requirements. A modest flight lift coefficient of 1.5 was assumed for takeoff. For the high speed cruise, sweep angles of 20º and 45º were considered. The lift coefficient of 2.3 is difficult to achieve without a low sweep angle, and the high speed cruise requires a highly swept wing to keep wave drag low. The constraint diagram shows the cruise constraint for both sweep angles.

If the wing had a fixed 20º sweep and the wing loading were about 40 lb/ft^2, all of the constraints would be satisfied with a thrust-to-weight ratio of about 0.6. This is a fairly low wing loading for an attack aircraft and would lead to an excessive takeoff weight. If the sweep were variable, though, the cruise constraint is no longer the limiting requirement (it is in the infeasible region of other constraints).

If the wing were allowed to sweep, the rate-of-climb constraint is the limiting factor. At a wing loading of 40 lb/ft^2, the required T/W is only about 0.35. This is a significant reduction and would have a great large impact on empty weight.

The required T/W can be even lower if the 500 ft turn radius constraint can be accomplished with morphing. One way to do this is to increase the wing area by about 20% and unsweep the wing to turn. At that point, the rate-of-climb constraint is not satisfied. But this is a temporary restriction until the configuration can change back. This is demonstrated in Figure 10 (Figure 9 zoomed in).

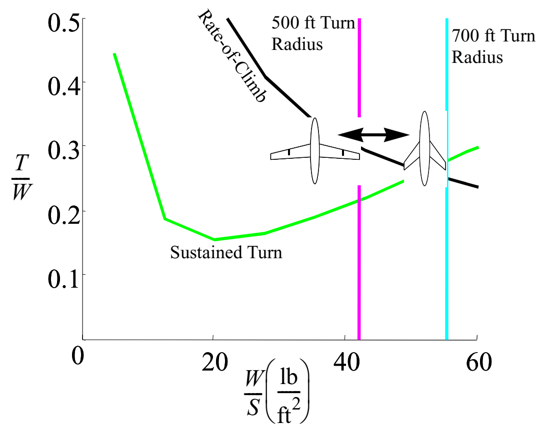

Figure 10: Morphing to Meet the Turn Radius Requirement and Keep the Wing Loading High

Figure 10 also demonstrates that changing wing area is not required if the customer is willing to accept a 700 ft turn radius instead of 500 ft (low sweep is still required to achieve a lift coefficient of 2.3). This is a perfect example of how customer requirements will dictate the level of morphing required. Additionally, if the cruise speed could be decreased to Mach 0.75 or so, a change in wing sweep may not be required. The vehicle at that point would not require morphing at all.

Conclusions

The promise of morphing is to allow aircraft to perform multiple missions with as little compromise as possible. Older morphing technologies have been in existence since the dawn of manned-flight but can not provide the revolutionary increase in capability necessary. The development of new structural concepts, materials, and actuators in the past decade may now enable the radical shapes changes necessary.

Morphing concepts were explored using birds as an example. Performance estimates were given for some of the bird-like morphing mechanisms including changes in wing area, camber, dihedral, and the effect of drag on the flight path angle in gliding flight.

The effects of morphing on the drag characteristics were explored using simple estimators appropriate at the start of the design process. The approach was to find the change in wetted area ratio to estimate the parasitic drag using equivalent skin friction coefficients and to modify the induced drag factor *k* by changing aspect ratio only unless suitable estimators for Oswald's span efficiency are available. More complicated drag estimators such as the component build-up method, which are easily automated on a computer, need no modification. A new drag buildup is simply done for each configuration, or the drag is recalculated as the components are allowed to morph.

A typical kinematic problem, turn radius, was explored considering variable wing loading and thrust vectoring as the morphing mechanism. Thrust vectoring is most effective at low speeds or at high wing loadings. The anecdotal cruise-climb problem was addressed with variable wing area. For configurations that are mostly wing, there is a clear benefit in changing wing area as fuel is expended. For configurations where the wing is not a majority of the vehicle wetted area, the issue is muddied because the drag characteristics change greatly. The cruise-climb problem will be moot in any case when free flight is fully implemented.

Finally, vehicle weight was considered. A cruise problem was established to determine the effects of changes in lift-to-drag ratio and specific fuel consumption on the vehicle weight through the fuel fraction. For typical commercial jets flying within the U.S., the change in weight is about 25% of the change in lift-to-drag ratio or specific fuel consumption. If the baseline lift-to-drag ratio is much lower, as would be the case for a fighter, the percent change is higher.

Fuel fraction is one component needed to estimate weight. Another component is system level parameters such as thrust-to-weight ratio and wing loading. The effects of morphing were shown on the constraint diagram, which graphically depicts the feasible T/W — W/S space.

The final component need for weight estimation is the empty weight. Since morphing aircraft are many aircraft, the empty weight for each configuration has to be considered. The empty weight expressions presented are technology barriers, meaning that the empty weight can always be greater but never less. Therefore, the empty weight of the vehicle is empty weight of the heaviest configuration in order for all configurations to be feasible.

References

[1] The Random House College Dictionary, revised edition. 1988.

[2] Daniel P. Raymer. Aircraft Design: A Conceptual Approach, 1st edition. American Institute of Aeronautics and Astronautics. 1989.

[3] John D. Anderson. Fundamentals of Aerodynamics, 2nd edition. McGraw-Hill, Inc. 1991.

[4] Richard S. Shevell. Fundamentals of Flight, 2nd edition. Prentice Hall. 1989.

[5] Nguyen X. Vinh. Flight Mechanics of High Performance Aircraft. Cambridge University Press. 1995.

[6] James Lighthill. Mathematical Biofluiddynamics. Society for Industrial and Applied Mathematics. 1975.

[7] R. McNeill Alexander. Animal Mechanics. University of Washington Press. 1968.