# New Aircraft Systems Concepts-Towards New Horizons in Aeroelasticity

**Terrence A. Weisshaar**
Purdue University
West Lafayette, Indiana

weisshaar@purdue.edu

## *ABSTRACT*

*During the past decade many new aircraft configurations have been suggested for military uses, primarily as the result of strong interest in unmanned air vehicles (UAVs). These configurations have included very high aspect ratio high-altitude flying wings, supersonic oblique flying wings, joined wings and finally, morphing wings that change shape drastically, often in a short time period equivalent to the short period mode of the airplane. These configurations have blurred the once clear boundaries between flight control and aeroelasticity and led to aeroelastic interactions that must be accounted for, particularly in the area of flight control. As a result, new tools are required to account for these interactions and to predict not only stability features of these complex designs, but to accurately predict loads. This paper will review briefly the trends towards innovative, aeroelastically challenging aircraft and concentrate attention on the recent development of morphing aircraft, the most challenging of the new configurations to appear in the last decade. Several new areas of research are suggested.*

## INTRODUCTION

Aircraft development has entered its second century; engineers now look back with pride and some awe to see how far they have come to produce airplanes that travel the globe reliably and efficiently at a wide range of altitudes at high and low speeds. History provides an abundance of examples of pioneers from all nations with vision, persistence and skill required to advance aeronautics. While technology and supporting developments such as analytical achievements have changed drastically, it is the creativity and initiative of scores of aeronautical scientists and engineers from numerous nations that have propelled aeronautical achievements forward.

This paper will focus on several likely future scenarios requiring multi-disciplinary aeroelastic analysis that is not fully developed today. Livne and Weisshaar[1] note that many aeronautical advancements were unplanned, unscripted or occurred in response to unforeseen problems; the aeroelastic experience of 100 years is too vast to be covered in a single paper. Although this is true, two excellent papers provide not only the history of the early days of aeroelasticity but also discuss the types of aircraft that tend to encourage or require new developments in analysis, testing or other kinds of developmental activities.[2, 3]

Aeroelasticity is by nature one of the premier multi-disciplinary engineering efforts of the past century. The conjunction of two diverse disciplines, aerodynamics and structural design, have been successfully merged to support aircraft development. When technical needs or developments add new components or capabilities to either of these disciplines, the shape of the airplane is likely to change, as it did when semi-monocoque metallic structures appeared in the 1920’s or when jet engines were introduced in the 1930’s. When airplane shapes, speeds or other performance related capabilities change, new problems with new needs appear.

No recent development is more typical or demonstrative of the type of future configurations requiring the aeroelastician’s attention than the so-called “morphing aircraft.” This paper will describe and summarize morphing aircraft technological progress so that we can forecast aeroelastic problems likely to arise from this type of configuration. In particular, this paper will discuss: 1) the need for morphing aircraft features at the systems level; 2) morphing component technology history; 3) technologies critical to future morphing development and success; 4) the results of the recently concluded design-build-test program conducted by the Defense Sciences Office of DARPA from 2002-2006, and; 5) prospects for the future.

U.S. Department of Defense DTO 71,[4] defines *morphing* as “a capability to provide superior and/or new vehicle system performance (e.g., agility/maneuverability, range, speed, acceleration, radar cross-section, payload/weapons and sensors, survivability) while in flight by tailoring the vehicle’s state (e.g., physical geometry/configuration, mechanical properties, electromagnetic properties) to adapt to the external operational environment (e.g., atmospheric, electromagnetic) and multi-variable mission roles.”

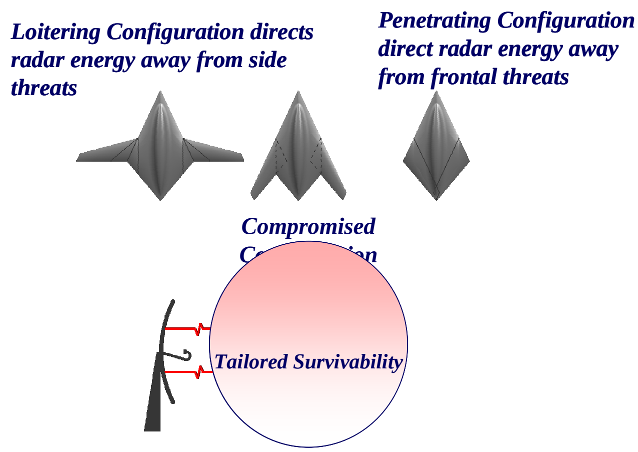


**Figure 1 – Morphing for survivability**

The DTO definition of “morphing” recognizes that there are situations where aircraft “state” is strongly related to its shape. Aerodynamic shape is an easy “state” to recognize. On the other hand, situations such as that shown in the cartoon in Figure 1 envision state changes that go well beyond those today. Changing radar signatures or “cloaking” in flight through re-shaping is well beyond what is possible today, but is not excluded from the future. From an aeroelastic standpoint and from a structural design standpoint, the designer is challenged by multiple structural states and the intermediate structural states that must be considered for a successful design.

Unlike military aircraft today, future Protean, multi-role morphing aircraft will change their external shape features *substantially* to allow systems to adapt to changing mission environments, including unanticipated threats or challenges. These physical features include re-shaping inlets, re-sizing wings and tail surfaces and re-shaping fuselage dimensions.

## The beginning of modern morphing aircraft – the vision of Clement Ader

The term “morphing wing” is used for a wide variety of different designs, in which the wing or portions of the wing change shape, usually by innovative arrangement of advanced materials and actuators. Although we will review a variety of these schemes, from the outset we want to be clear that the type of morphing to be discussed is confined to large wing dimensional shape changes that in turn create demonstrable changes in system performance.

Figure 2 - Clement Ader's *Eole* – a (non-flying) shape

When reviewing the history of morphing aircraft, one is reminded of the Biblical verse, *"What has been will be again, what has been done will be done again; there is nothing new under the sun."* (Ecclesiastes 1:10) although the author of that verse forgot to mention that clever government program names and acronyms can disguise this fact. Early aviation enthusiasts watched birds soar, changing wing shape as they dove and loitered. On the basis of his observations, in 1890, the French aviation pioneer Clement Ader proposed the wing morphing design shown in Figure 2.[5] He developed ideas for the future of aviation warfare and described them in a monograph published in 1909.[6] Consider his description of the general military airplane and in particular, the Scout aircraft:

*"Whatever category airplanes might belong to, they must satisfy the following general conditions:* ***their wings must be articulated in all their parts*** *and must be able to fold up completely…* ***When advances in aircraft design and construction permit, the frames will fold and the membranes will be elastic in order to diminish or increase the bearing surfaces at the wish of the pilot****…*

*…Their wings will be bat-type or preferably bird type, long and narrow, with the minimum of surface and hence a heavy load for each square meter.* ***Moreover the wings will be adjustable, so that in flight they can be reduced by a half or a third or even less****…"*

*…"The wings will be extendable in flight and their surface will be increased or decreased at will. These airplanes will be characterized by their agility but will also be of solid construction. To strengthen their framework, both in bat and bird-type construction I propose to make some of them of metal, following experiments and plans already made. Because these airplanes will be stored in great numbers, their wings will fold up completely with great ease…"*

Given Ader's lack of aeronautical knowledge, the paucity of analytical tools and the interesting, but limited vision of future uses, these ideas were at the level of Jules Verne science fiction. However, Ader's brilliant vision anticipated by several decades the development of morphing wing aircraft and, by chance and observations of bird flight, accurately described why and how these wing re-shaping worked at the systems level.

## A systems approach to creating capabilities-how can we make the system less complex?

Aeronautical systems, particularly military systems, comprise a system of systems (SOS). Within this SOS there are usually several different aircraft, fighters, bombers and tankers for instance, and spacecraft systems, such as Global Positioning systems and communications links, that are inter-linked to provide a capability required for the military to execute its mission.
Within the SOS there are many specialized components. Specialized fighters, long range bombers and reconnaissance aircraft are at the heart of an Air Force attack system. Once a system and its components, such as a specialized airplane, are defined, designed and built to meet a concept of operations (ConOps), it is difficult to respond to unforeseen or radically changed operational needs. One such problem occurs when a need develops to acquire and destroy time-sensitive, rapidly moving targets that are a great distance from an

operational base. "Make-do" or jury-rigged systems are possible, but such a solution may be expensive and have built-in inefficiencies even in the best situations.

Raymer[7] lists five fundamental aerodynamic features that strongly determine aircraft performance. These parameters are: wing loading (denoted as W/S, the ratio of aircraft weight, W, to wing reference area, S); wing thickness-to-chord ratio (denoted as t/c); wing planform taper (denoted as λ, the ratio of wing tip chord to wing root chord); wing span (denoted as b); and wing sweep (denoted as Λ).

Airplane drag determines the engine size and fuel required and drag depends on wing area. Drag also depends on the overall aircraft surface area, called the wetted area, composed of wing, fuselage and tail area. To understand how shape changing can affect aircraft drag, consider Eqn. 1. This relationship provides an idealized expression for aerodynamic drag for an airplane with weight *W*, operating at a *subsonic* flight speed *V* and an altitude with an air density $\rho$ is written as

$$Drag = thrust\ \ required = qC_f S_{wet} + \left(\frac{1}{q\pi e}\right)\left(\frac{W}{b}\right)^2 \qquad (1)$$

Eqn. 1 shows that drag is a function of $q = \rho V^2 / 2$, the wing span, b, the total wetted area $S_{wet}$, the surface friction coefficient, $C_f$, and a parameter known as the Oswald efficiency factor, e.

The first term in Eqn. 1, the "parasite drag," approximates the effects of skin friction on creating air resistance. The second term, the induced drag term or "drag due to lift," is a function of span loading, W/b.

Eqn. 1 does not include the wave drag term which becomes very important at transonic speeds. Wave drag depends primarily on wing sweep, thickness-to-chord ratio and camber. Eqn. 1 also does not include pressure drag generated by flow separation from protuberances such as small antennas or discontinuities in outer surfaces. For airplanes designed for high speed flight, the parasite drag (including wave and pressure drag components) is so important that minimizing the vehicle surface area is a prime design configuration concern.

Since for any flight condition, lift equals weight and drag equals thrust, the lift to drag ratio, L/D, is a function of weight and flight speed. However, the *maximum* L/D ratio is a function only of the shape of the airplane outer mold lines, as shown in Eqn. 2.

$$\left(\frac{L}{D}\right)_{\max} = \frac{b}{2}\sqrt{\frac{\pi e}{S_{wet} C_f}} \qquad (2)$$

Changing the shape by changing/morphing the aircraft geometry will change both the drag and the maximum L/D. The ratio of the maximum unmorphed L/D to the morphed L/D ratios is

$$\left(\frac{L}{D}\right)_{\max} \Big/ \left(\frac{L}{D}\right)_{\max}^{Morph} = \frac{span}{span^{Morph}}\sqrt{\frac{S_{wet}^{Morph}}{S_{wet}}} \qquad (3)$$

Note that changing wing span has a strong effect on L/D, while changes in the airplane surface area are diminished by the square root operation in the right hand term.

If the ever-popular camber is used as a morphing design feature, it does not have an impact on basic L/D increases at this level. What does have an effect is the ability to change wing span or wetted area. Camber is not a non-useful design parameter, it is simply not a primary design sizing parameter.

Morphing comes at a cost and the cost is complexity and weight for morphing devices. Aircraft take-off gross weight (TOGW) is the sum of three weight components

$$W_{TOGW} = W_{empty} + W_{fuel} + W_{payload} \qquad (4)$$

Adding weight to any one of these three components can add or subtract weight from others. Reducing the weight of fuel, or the engine weight by adding devices to increase aerodynamic performance can reduce the take-off gross weight (TOGW) if the airplane operates for substantial times in the mission segment affected by the aerodynamic performance change.

As indicated in Figure 3, retractable landing gear are one of several morphing devices added to an airplane system to reduce high speed drag. Their addition adds from 3-5% of the TOGW to a design but decreases the requirements for engine thrust and fuel during high speed cruise, thus reducing the TOGW itself. This is a net win for the system.


**Figure 3 –Modern morphing components for high performance aircraft**

We have other morphing devices used to improve the system by adding weight in one category, for one part of the mission, but reducing it in another.

## A brief history of morphing wings

The number of early aircraft designs that could be classed as "morphing aircraft" is large. The early designs with morphing features certainly include the Wright Brothers' wing warping and Bleriot's Antoinette designs which featured controlled wing twist also. Some of these Bleriot designs also suffered from static aeroelastic problems due to the structural flexibility required by the wing twist.

However, in keeping with the DTO 71 definitions that morphing *"provide superior and/or new vehicle system performance … by tailoring the vehicle's state … to adapt to the external operational environment … and multi-variable mission roles"* we will discuss a limited set of historical examples that reinforce the value of this definition and concept.

Several early morphing aircraft designs provided good low speed and high speed performance, typically allowing large wing area to create very low landing speeds but also allowing smaller wings with less drag at high speed cruise. These first wing designs were unswept and operated at relatively low speeds, even at "high speed" cruise.

Ivan Makhonine, an expatriate aircraft designer from the Soviet Union, developed the telescoping wing MAK-10 that first flew in August 1931.[8] This morphing wing concept has appeared in many different designs since then. Telescoping wing designs allow large changes in wing span and wing area, but require only simple mechanical designs and mechanisms.

Makhonine's telescoping wing had three major parts that slid over each other to change the wing span and area: in operation, this airplane changed wing span 162% (from 13 meters to 21 meters) while the wing area changed 157% (from 21 to 33 square meters). Pneumatic actuators provided the energy for extension and contraction. The wing loading was about 30 lb/square foot and the airplane was considered to be underpowered, with a maximum speed of 186 mph with the wings retracted and 155 mph with the wings fully extended. Makhonine designed other successful variable-geometry aircraft. His last, the MAK-123, was first flown in 1947 in France and demonstrated extension retraction of telescoping wings with no adverse effects.[9]

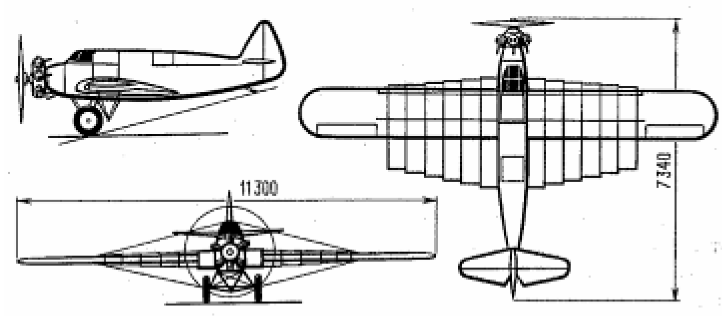


Figure 4 - Bakshaev LIG-7

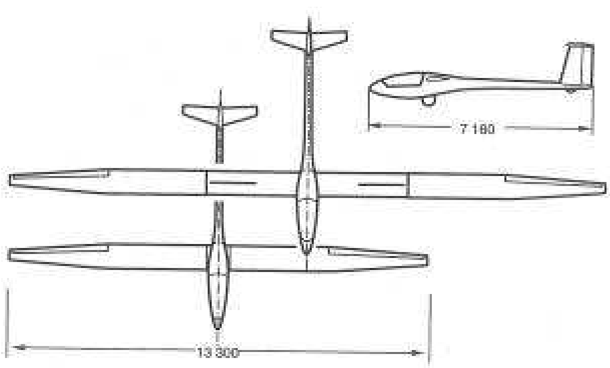


Figure 5 - The fs-29 planform geometry with side view

The MAK-10 inspired designers Georges Bruner and Charles Gourdou to design a small aircraft named the G-11 C-1. This airplane was never built, but its design had a wing whose area could range between 11.4 and 17.2 square meters with spans between 6.76 and 11.4 meters. Range was predicted to be 466 miles at 310 mph with outer wing panels retracted and 1243 miles at 149 mph with wing panels extended. In the end, the two designers determined that this telescoping scheme was impractical for an airplane as small as theirs; they abandoned their idea.[10]

Figure 6-German fs-29 sailplane

The Bakshaev LIG-7, an unusual and innovative morphing aircraft with two-dimensional in-plane operation, was developed in the Soviet Union in 1937.[11] This aircraft, shown in Figure 4, had a high-aspect-ratio wing designed for efficient cruising flight. For take-off and landing, six broad-chord wing sections were extended from the fuselage to 2/3 of the wingspan. Each wing section, 50 cm. wide, was made of plywood, with a support rib on the inboard side and a light frame on the outboard side. The telescoping wing sections were retracted and extended by tensioned steel wires, operated manually from the cockpit. All retractable sections were completely hidden inside the fuselage when retracted.

During 1937, flight tests showed that wing retraction (requiring from 20 to 30 seconds) and extension (requiring from 30 to 40 seconds) was easier to perform in-flight than it was on the ground. No handling peculiarities were observed.

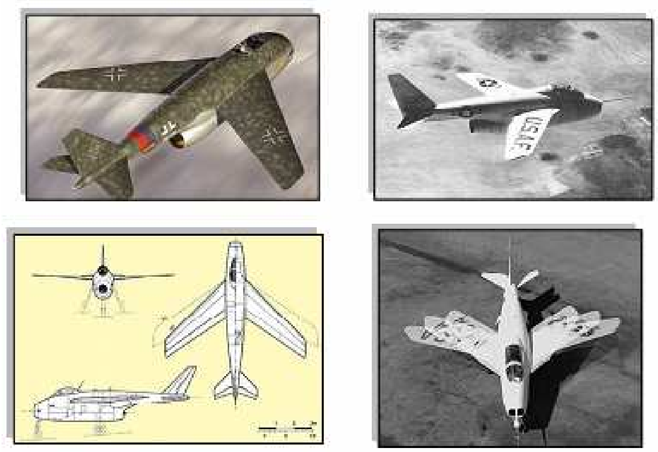

**Figure 7 - From left: Me P-1101 drawings, Bell-X-5 in-flight and on the ground**

According to observers, the effect of wing morphing on take-off and landing characteristics was impressive and reliable. On the other hand, the morphing impact on performance was not significant for this small and slow aircraft (the wing contributed only 20% of total drag).

The IS-1 fighter, designed by Nikitin-Shevchenko in 1932, was notable in that it did not telescope to change span. This design used out-of-plane displacement to change its configuration from a bi-plane operating at low speed to a monoplane operating at high speeds. Most of the lower wing folded into the fuselage to reduce the wetted area to create a design that resembled a monoplane with a small canard surface.

A modern sailplane, the German fs-29 glider, shown in Figure 5 and Figure 6 provides a good example of a morphing telescoping wing to improve soaring performance.[12] "Performance soaring" requires an aircraft to cover a given distance in the shortest possible time. To do this, the sailplane must operate at two different speeds, depending on whether it is in the cruise or climb mode.

The extendable structure must resist binding under load, particularly when wing deflections are relatively large at high load factors. The fs-29 uses pilot cranking to extend or retract the wing outer surfaces.[13]

Variable sweep was introduced by morphing aircraft designers to address the trade-off that must occur between wing mechanism complexity, weight and performance at high and low speeds. Modern variable sweep aircraft trace their origins to the Messerschmitt P-1101 design which appeared in Germany in 1944 but never flew there. After World War II engineering plans for the P-1101 were used to develop the Bell X-5, variable sweep aircraft. These two designs are shown in Figure 7.

**Figure 8-F-111 aircraft with vortex generator deployed to improve flow**


**Figure 9 – Grumman XF10F Jaguar**

The interest in variable geometry wings in the 1950's and 1960's arose because of aerodynamically dissimilar mission objectives that were difficult ot achieve without wing morphing. These objectives included the requirements for: 1) long-range subsonic cruise or long-endurance on station; 2) high supersonic speed interception and low-altitude transonic strike; and, 3) operation from limited length runways (or aircraft carriers). Without wing sweep change during each of these mission segments, the fixed-wing compromise is nearly always heavier than a variable-geometry, morphing wing.[14]

The learning exercise - what to do and what not to do - with both the X-5 and the Grumman XF10F Jaguar (shown in Figure 9) were important steps towards modern morphing aircraft. Both aircraft placed the wing pivot near the wing root. While this placement reduced wing wave drag at high speeds, it also introduced the requirement for a larger tail to control the nose-down pitch created by aft aerodynamic center movement. This aft movement became even worse when the aircraft flew into the supersonic flight regime.


**Figure 10 – Boeing 2707-200 supersonic transport**

The Bell X-5 did things differently because it used an internal rail system within the fuselage as well as a wing pivot. As the wing was swept back, the pivot moved forward to compensate for the aerodynamic center shift. This required a heavy mechanism and a larger fuselage with larger parasite drag. The NACA later developed an outboard pivot with a glove area inboard to minimize the aerodynamic center travel by redistributing the longitudinal lift distribution as the wing was swept.

The F-14 Tomcat is the most successful American variable sweep military aircraft. Grumman pursued a fixed wing F-14 design and tried to reconcile the conflicting requirements of high maximum Mach number, subsonic loiter and carrier suitability but found that this required a larger wing area and a higher thrust to weight ratio, making the fixed wing design considerably heavier (about 4500 lbs. heavier).[15] This aircraft was later joined in the military fleet by the B-1 bomber. Variable sweep was also used on the Soviet Union's Tupolev-22 (Blackjack) supersonic bomber and the MiG-23 fighter.

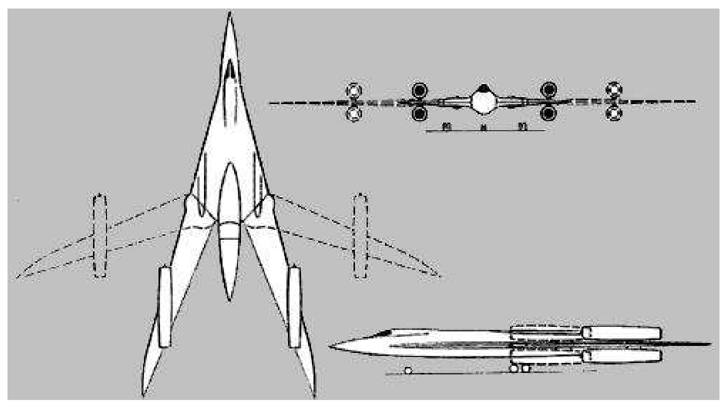

**Figure 12 - Barnes Wallis Swallow supersonic passenger aircraft**

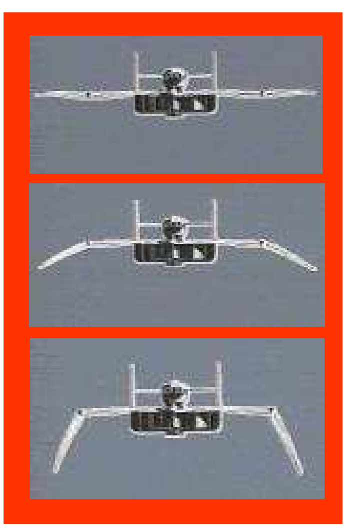

**Figure 11 – XB-70 Bomber**

In addition to the added weight of pivots for variable sweep wings, leading and trailing edges must be housed within a cavity in the complex wing structure. Figure 8 shows the vortex generator deployed in front of the wing cavity for the variable sweep F-111 aircraft. The F-14 uses air-bags to create an aerodynamic seal and a smooth external contour when the wing is re-positioned.

Commercial morphing aircraft designs also appeared in this time period. The Boeing 2707 Supersonic Transport, shown in Figure 10 as it was proposed in 1964, used variable sweep as a feature to reconcile the low landing speeds required with supersonic flight. The Boeing 2707 would have been able to operate efficiently over populated areas at low speed without sonic booms. The design was selected in 1966 as the winner of a selection process involving Boeing and Lockheed.

Boeing abandoned its variable sweep design in 1968 after wing/tail integration difficulties. On September 23, 1969, President Nixon approved a fixed wing design for construction. The U.S. Senate weighed in on March 24, 1971 and cancelled the project.[16]

An even earlier design, a supersonic transport shown in Figure 12**, w**as proposed in the early 1950's by the British engineer Sir Barnes Grenville Wallis. This airplane used variable sweep for aerodynamic performance and flight control.

At about the same time, the XB-70 supersonic bomber, shown in Figure 11, successfully incorporated three-dimensional wing morphing by folding its outer panel downward almost 30$^o$ to control and improve L/D at both low subsonic and supersonic speeds. The design operated a speeds exceeding Mach 3 and in a challenging high temperature environment. Although the weight for the structural fittings and actuators required several tons of material, the XB-70 design is the most successful, challenging use of a morphing wing surface design to improve performance in multi-Mach number flight regimes.

Although we have emphasized that wing camber is not one of Raymer's Basic Five conceptual design parameters, variable camber improves fighter arcraft performance at all flight conditions because airfoil cross-sectional shape controls the chordwise pressure distribution. The F-16 and F-18 aircraft use discrete leading edge and trailing edge flap deflections to control camber, although imperfectly. An ideal wing design changes shape like a bird without opening gaps, slots or steps on its surface. Wing camber morphing creates a variety of wing cross-sectional shapes that control drag by: 1) maintaining smooth flow at high angles of attack at low speed; and, 2) controlling the formation of shock waves of wings at transonic speed.


**Figure 13 – AFTI/F-111**

No review of historical wing morphing efforts is complete without mentioning the highly successful Mission Adaptive Wing Program (MAW).[17] The MAW project, begun in the mid-1970's, produced wing camber changing concepts and flight articles that were tested under a variety of challenging conditions, including a flight demonstrator, the AFTI/F-111, shown in Figure 13.

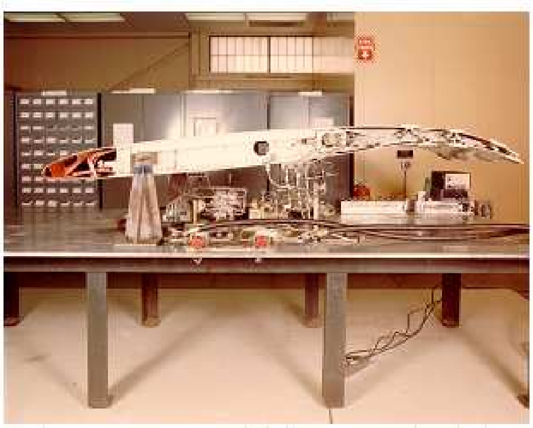

**Figure 14 - MAW airfoil cross-section in its deformed, cambered position**

The MAW variable camber device, shown in a test fixture in Figure 14, created camber with an internal mechanism that bent the wing trailing edge region. This region consisted of three regions with upper and lower fiberglass surfaces. This deformation created optimum camber over a wide range of airspeeds from low subsonic to supersonic flight.[18,19] Flight tests conducted in the 1980's, ending in 1988, confirmed the superior aerodynamic performance predictions and control of the MAW assembly over a wide speed range.

# EXPANDING NEW SYSTEMS CAPABILITIES - NEW AIRCRAFT SOLUTIONS

Morphing designs have been proposed for a wide variety of missions, but the most prominent of these has been the attempts to reconcile low speed requirements with high speed performance. This brief introduction shows that there is a history of innovative morphing aircraft systems development and the materials, design and control technologies that support it.

Wing area changes are created either by rearrangement of parts of the wing, through in-plane movement of large portions of the wing – variable sweep is one successful example – or by out-of-plane movement of portions of the wing such as seen on the B-70.

Despite the remarkable development of new materials, sensors and actuators, it is unusual that we have not seen more "morphing aircraft" develop. Figure 15 depicts the large number of variable sweep wings (and the B-70) that entered the world's military aircraft inventory over a period of 30 years. This figure also shows that this number declined rapidly after increasing rapidly.

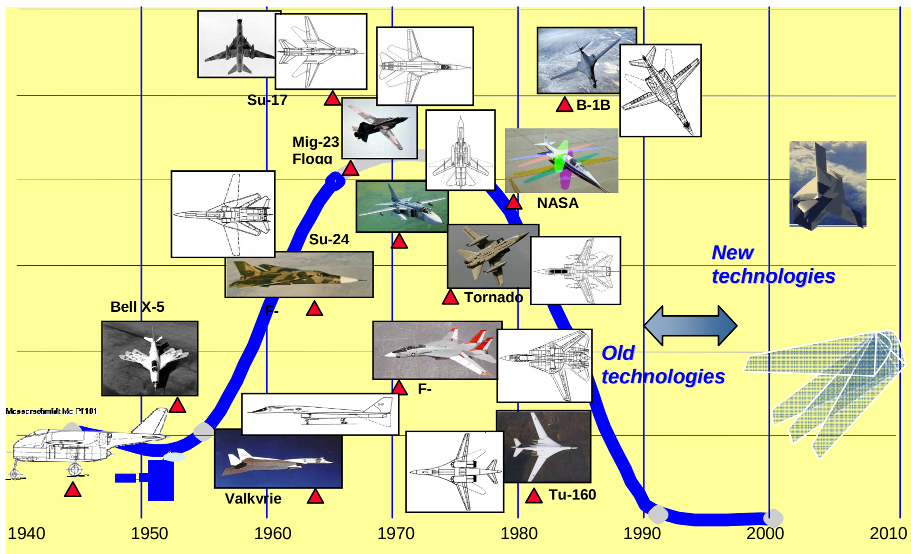


**Figure 15 – Variable sweep morphing wings**

Morphing aircraft are distinguished by their ability to change aerodynamic and geometrical features to respond to different or uncertain mission environments. Morphing efforts have been confined primarily to wing design, but is fair to ask "in the future, how will the general morphing aircraft concept increase military capabilities – and – what morphing features should I develop?"

Available literature concerned with future U.S. Air Force, Army and Navy objectives indicates that future systems will be required to: 1) provide capability against elusive, highly mobile targets; 2) have more kills per sortie due to limited windows of opportunity; 3) provide multi-role flexibility; be low observable; 4) operate unmanned, but with manned aircraft as part of the package; 5) operate on a co-mingled battlefield (friendly/enemy; combatants/non-combatants).

From this future capabilities assessment, it seems that it would be desirable to develop systems that can search, locate, target and attack both air and ground targets, but can also survive and persist in the face of enemy opposition. Note that the term "systems" is used here, not "aircraft" since the system components consist of a variety of aircraft and ground based or sea based components linked together.


**Figure 16 – A systems approach to determining the worth of morphing aircraft**

A key feature of the system air vehicle component is the emphasis on survivability and speed as protective measures and the ability or stand off from defended areas. However, if the aircraft stands off too far, then it becomes unresponsive to some types of moving, “pop-up” targets and cannot effectively operate on the “co-mingled battlefield.”

Figure 16 shows the systems trade-off and quandary. Two scenarios are presented. The first is a situation in which there are few targets and more hunters than killers are required. The second scenario is one in which more killers than hunters are required. However, since the system is required to address both situations, a total of 10 hunter and ten killers are required, for a total of twenty airplanes. If the hunter/killer features can be combined then only 12 airplanes are required.

Future aircraft systems must operate over a wide range of speeds from low subsonic to high supersonic. Many of these capabilities have been demonstrated in the past on flying vehicles of one size or another. Morphing adds the ability to change planform area, wing sweep, wing span, fuselage size and tailor inlets. However, technical challenges that include a range of efforts from developing new materials and actuators to developing new analytical methods that allow combining these capabilities to create effective designs.

## Morphing wing design challenges

The central morphing wing challenge is to create design, fabricate and operate effective integrated combinations of deformable wing skins, actuators and mechanisms, structures, and flight controls to provide an aircraft system designer the freedom to deal with future diverse, conflicting vehicle mission capabilities. Wing cover skins must be highly deformable, but still maintain their shape and structural integrity under compression, tension, shear and bending characteristic of aerodynamic and flight loads. New materials being investigated to meet those requirements include shape memory polymers and elastomers, as well as hybrid composites.

Actuators must meet size/weight/volume, power, force, displacement, and bandwidth requirements. Mechanisms must provide a controlled range of motion with limited binding/friction. Innovative devices such as thermal active polymers and advanced piezoelectric actuators are being developed to meet these needs. The flight control system and software must be able to adapt to radical shape changes as well as to reconfigure control effectors appropriately for the configuration. New flight control approaches are under development to achieve these requirements.

# The DARPA Morphing Aircraft Structures (MAS) Program

Morphing military systems provide agility (the ability to take on new roles), robustness and time responsive action. Shape morphing components such as wings, fuselages and engine inlets, allow aircraft to maintain near optimal operational features and a high level of performance while undergoing predictable or unpredictable, real-time changes in operating conditions.

The two-phase DARPA program to develop morphing wing structures (identified with the acronym MAS) to operate over a wide range of airspeeds, up to transonic speeds at high altitude, was completed in early 2006 and transitioned to a brief demonstration phase that saw the design of small flying demonstrator models. DARPA/MAS had two primary technical goals: (1) to develop active, light-weight wing structures that change area and shape substantially, to provide a wide range of aerodynamic performance and flight control features not possible with conventional wings; and, (2) to enable development of air vehicles with advanced capabilities not achievable with conventional aircraft.

During the MAS program, two DARPA-funded contractors designed, manufactured and tested large scale, robotic, morphing wing designs that demonstrated structural integrity and operation in a wind tunnel environment. Testing was done at the NASA Langley Research Centre Transonic Dynamics Wind Tunnel (TDT) in Hampton, Virginia. The key challenge for this program was the controlled increase in wing span and wing planform area, sufficient to improve the mission performance and agility by measures up to 50%, using a wide range of advanced technologies that included seamless, adaptive skins, novel actuators and mechanisms, and advanced flight controls.

Successful integration of these technologies was demonstrated in a step by step process that used bench-testing, with simulated flight load conditions, and a difficult wind tunnel test matrix that successfully demonstrated proof of concept. These tests also generated the information necessary to design a scaled morphing UAV demonstrator.

In January 2003 the Defense Advanced Research Projects Agency, DARPA, launched a research development whose objectives were to design, build and demonstrate active, variable-geometry wing structures with the ability to change wing shape and wing area substantially.

**Figure 17 – NASA morphing vehicle concept**

The MAS effort was an extension of activities that began in the early 1990's with DARPA's development of smart materials and devices. This effort was due to Dr. Robert Crowe, then a Program Manager in the DARPA/Defense Sciences Office (DSO). He followed this materials development effort with demonstration projects such as the Smart Wing Program, SAMPSON (an advanced inlet morphing program), and the Smart Rotor Program. A follow-on effort, the Compact Hybrid Actuator Program (CHAP), was developed by Dr. Ephrahim Garcia during his tenure as a DARPA Program Manager.

Significant morphing wing efforts were also part of NASA Langley Research Center's Morphing Aircraft initiative which produced advanced "smart" actuators to control flow and also resulted in design concepts such as that shown in Figure 17.

The DARPA MAS program began with three contractors--Lockheed-Martin (Palmdale, California), Hypercomp/NextGen (Torrance, California) and Raytheon Missile Systems (Tucson, Arizona). All three MAS contractors believed that large wing planform area changes and wing span increases were primary enablers of a new class of morphing air vehicles with; 1) responsiveness – time critical deployment with the ability to respond to unpredictable crisis situations; 2) agility - the ability to change system roles on demand – this included the ability to change from a hunter/searcher to a "killer"/destroyer or from an ISR asset to a communications node; 3) persistence - the ability to dominate large operational areas for long time periods.

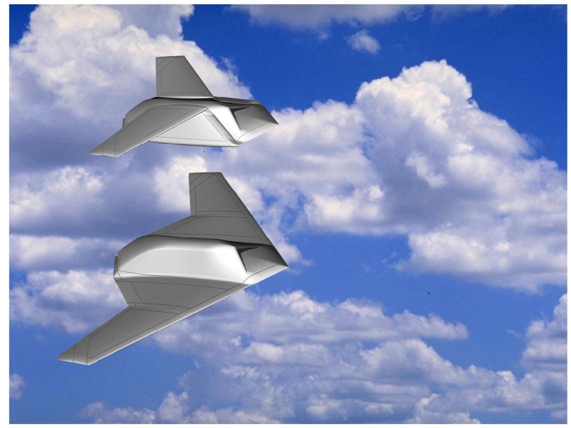

Figure 18– Lockheed-Martin folding

Lockheed-Martin developed the design concept shown in Figure 18 to change wing performance by folding wing panels into the fuselage. This folding wing approach, reminiscent of the folding B-70 concept, "hides" a substantial portion of the wing area during the low altitude, transonic dash portion of its mission. This design uses advanced skin materials in the wing fold regions to maintain surface smoothness when the wing folds in flight.

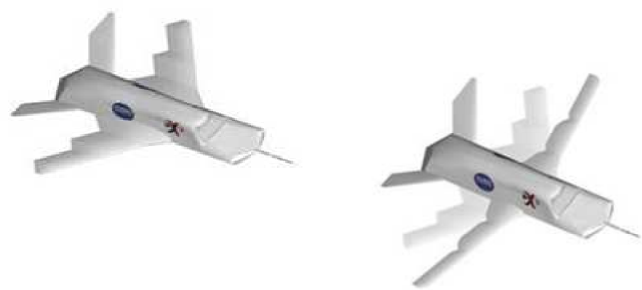

Figure 19– NextGen morphing wing concept

NextGen Aeronautics, led by its president, Dr. Jay Kudva, developed the design concept shown in Figure 19, with the ability to create substantial in-plane shape changes and surface area reduction to transform the wing from an efficient, high-aspect-ratio loiter shape to an efficient, swept, reduced-wing-area transonic, low altitude dash shape.

Raytheon designed a cruise missile telescoping wing, shown in Figure 20, to change the wing area and span by 50%. This design challenged packaging of actuators and additional structural mechanisms to fit within a very small volume in the missile. The design also increased the loiter time in the target area.

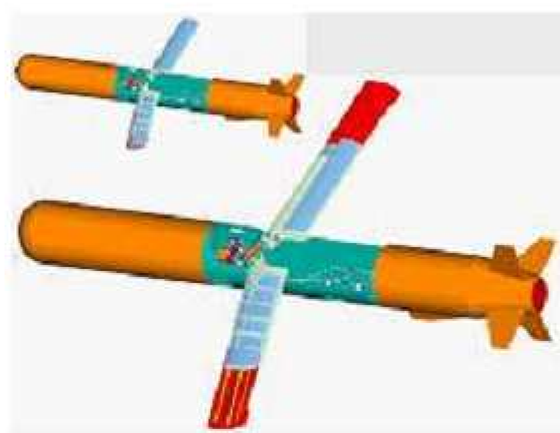

Figure 20 – Raytheon morphing wing design

## Materials, actuator selection & mechanism design

The fundamental challenge to shape changing structural design is to create structures and components that resist external loads, yet can exhibit large dimensional changes on-demand to perform multiple, drastically different, functions or mission roles. To limit the size and weight of actuators, the forces and moment, as well as the amount of energy required to move from one position to another must be small.

Morphing poses two additional challenges when the wing loading is high. While the wing structure must have high bending and torsional stiffness, it must also be very compliant to allow actuators to change structural geometric features with low force and moment input. Very flexible materials are the designer's first choice for these compliant regions. However, flexible skin surfaces, like Ader's bat wings sag under surface pressure loads and torsional stiffness is degraded. Finally, preventing the active, shape changing mechanisms from binding or "sticking" as they move from one position to another challenges designers.

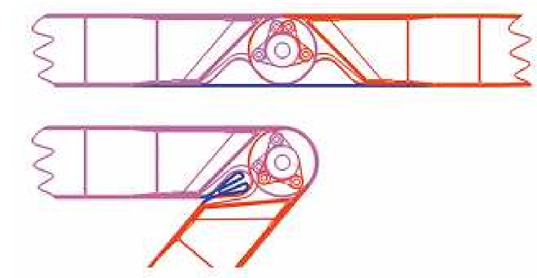

Figure 21– Lockheed-Martin elastomeric skin and joint design

An example of how these problems were overcome is provided by the Lockheed-Martin design. When a wing such as that shown in Figure 18 is folded, the skin material surrounding the wing joint develops large strains on the upper part of the outboard wing joint while the material on the lower potion of the outboard wing joint is compressed and retracts into the wing joint, as shown in Figure 21. On the other hand, while advanced elastomeric materials are a good choice for this skin, polymer elastic properties at high-altitude, low temperature conditions are not well-documented. In addition, the lower surface skin must be controlled to make sure that it folds into the wing joint. As a result, the system required for surface skin control provides a weight penalty.

Actuator power and force capability to move portions of the wing from one point to another are essential. The size, weight and volume of the actuators are important metrics, as is range of motion, bandwidth and fail-safe behavior. Wing mechanism locking is also essential when the morphing wing is loaded. Internal control to move from one wing form to another is an important design goal. This involves sensor selection, braking and locking and the integration of sensors, actuators and the software to link them.

Finally, the speed at which morphing shape change occurs is a significant design parameter. While slow, quasi-static changes may be sufficient for some missions, rapid changes to increase aircraft maneuverability will make future morphing aircraft even more capable. Adding flight control to the list of morphing attributes is a future challenge.

# Morphing challenges

The DARPA MAS program tests demonstrated the following: 1) the ability to create lift and reduce drag over a wide range of flight speeds from low subsonic to transonic speeds and altitudes from sea level to 50,000 feet; 2) the ability to repeatedly sustain and transfer external and internal loads without excessive deformation, binding, fracture or aeroelastic instability; 3) a design with aerodynamic shaping features to support future advanced system capability; and, finally, 4) creation of designs that displayed innovation, creative mechanism design.

These objectives required: 1) the ability to move the wing accurately from one position to another under a wide range of external aerodynamic loads; 2) low mechanical complexity as measured by the number of joints and mechanisms required; 3) self-contained power and power distribution; 4) light weight design with self-contained actuation units.

Both contractors built wind-tunnel models that fulfilled the program objectives. A key feature of these models was the requirement to include all mechanical and power systems within the models themselves. Structural integrity tests were conducted at the NASA Langley Research Center Transonic Dynamics wind tunnel (TDT) in Hampton, Virginia. Pre-test activities included: 1) integrated wing component element bench top testing with representative loads applied; and, 2) construction of actively controlled morphing wings for wind tunnel testing under flight loads, including aeroelastic effects to demonstrate wing shape control and aerodynamic performance.

The maximum cross-sectional dimension of the TDT is 16 feet; this is a size constraint for the maximum model size without introducing blockage or tunnel wall interference. NextGen and Lockheed-Martin models were large, making them among the largest heaviest models tested in the nearly 50 year history of the TDT. With instrumentation, both model weights exceeded 1000 pounds, although the wing weights themselves were substantially less.

Although the TDT tests met DARPA requirements and NASA TDT constraints, wind tunnel testing cannot provide a test of all design parameters. Early in the test planning process the DARPA Phase 2 objectives had drag reduction demonstration as an objective. Drag measurements were not part of the final test data due to wind tunnel mounting constraints.

## NextGen Aeronautics wind tunnel model and tests

NextGen Aeronautics reconfigurable wing model had the ability to move between five different wing planforms shown in Figure 22. The design incorporates wing planform changes in area, span, chord, and sweep that vary by 51%, 36%, 110% and 30 degrees, respectively. The model size was representative of a full-scale UAV with a gross take-off weight of approximately 2400 lbs. The test conditions were representative of flight altitudes varying from sea level to 50,000 ft and Mach numbers up to Mach 0.92.

The NextGen wing design incorporates innovative features that include: 1) flexible skins to undergo strains in excess of 100% but still transfer airloads to the wing internal substructure; 2) a kinematic sub-structure with joints to enable morphing wing geometry changes; and, 3) distributed actuators that power morphing geometry changes. The five model planforms were subjected to 1200 lb lift loads and the accompanying drag loads.

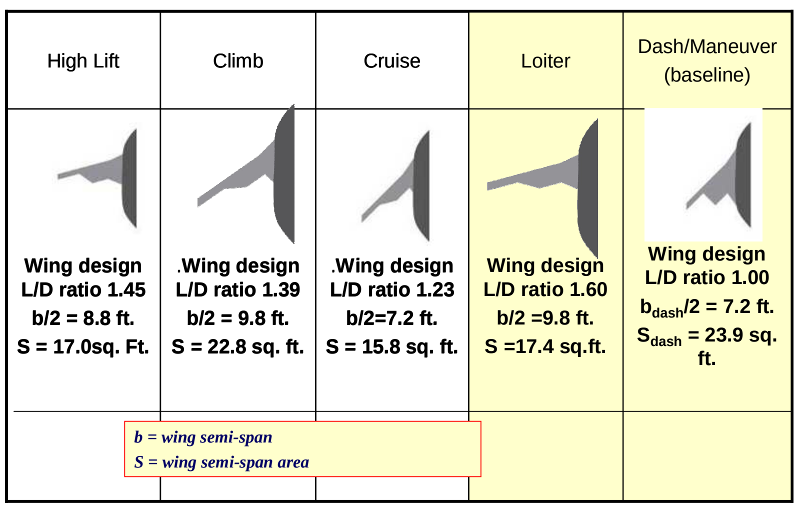


**Figure 22 – NextGen morphing wing planform configurations**

The underlying principle of NextGen's innovative concept, shown in Figure 23, is an adjustable framework to allow in-plane reconfiguration of highly flexible skins and internal components that create wing area and span changes, including changing leading edge sweep to control aerodynamic drag. The framework has four attachment points located on the fuselage. The wing surface area, sweep and span is controlled by selectively constraining one or more points at the wing root attachment to the rail while others are moved by hydraulic actuators,. The NextGen "endo-structure" has replaced the traditional semi-monocoque "exo-structure." To torsionally stiffen the wing, a tubular leading edge shell component was added.

During the TDT tests, the wing logged 25 "flight" hours and underwent 51 morphing cycles at a variety of flight speeds and altitudes. The tests confirmed the ability of the morphing models to move smoothly from one position to another under load and to control accurately the planform shape. The tests also confirmed the absence of aeroelastic instabilities as mechanisms were locked and unlocked.

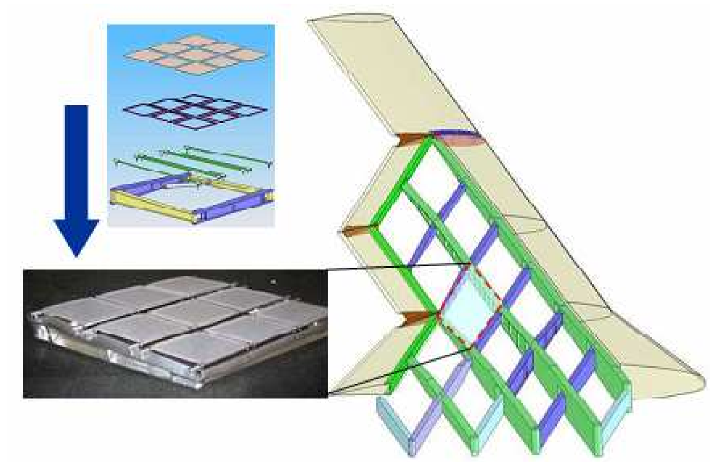

**Figure 23 - NextGen morphing wing mechanism concept showing flex-skin cover panel arrangements**

The NextGen TDT model stress analysis used computational fluid mechanics for aerodynamic loads generation coupled to finite element structural analysis. Flutter computations were conducted with finite element analysis coupled to vortex lattice aerodynamic panel methods. However, modeling of joint friction and the ability to optimize actuator location was minimal because of the absence of effective analytical tools. Similarly, the absence of an aeroelastic analysis capability to model the dynamic response of a moving structure in low speed or high speed flow created additional uncertainty. Wind tunnel testing addressed these uncertainties, but added risk.

The MAS pre-test program was divided into two parts: 1) proof of concept demonstrated without the skins; and, 2) ground vibration testing (GVT) with the flex-skins attached. Three potential "show-stoppers" were of concern to DARPA and NextGen engineers. First of all, there was some concern that the moving mesh design might develop joint free-play. Joint free-play can lead to aeroelastically induced vibration, including flutter. This is an analytical problem for which there is no good analytical tool for this analysis.


**Figure 24 – NextGen model mounted in TDT**

The second potential problem is the fact that local flexibility of the skins and their nonlinear behavior can introduce unanticipated localized stresses. Flex-skin tearing at high speeds can lead to model destruction. Finally, as the wing moves from one position to another the stiffness and the aerodynamic loads change rapidly. This provides an opportunity for a self-induced aeroelastic instability or interaction with the wing mesh control system. No analytical techniques to address this morphing wing phenomena exist, hence the importance (and risk) of testing.

Figure 24 shows the NextGen morphing model mounted to the TDT wall surface. This mounting requires a balance system to feed the loads from the model to measurement and model control devices on the other side of the wall.

The model weight, the lift and pitching moments produced during testing excluded all but two possible wind tunnel balances. Neither of these model balances accurately measured drag, but structural integrity, not aerodynamic performance was the primary issue for these tests.

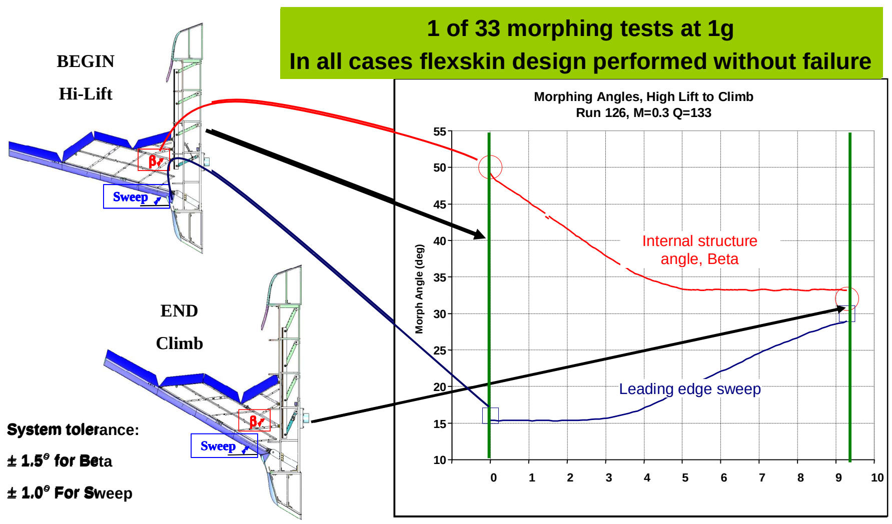


Figure 25 - NextGen TDT model performance showing smooth mechanical operation with accurate wing sweep control

TDT measurements to compare to analysis included actuator force levels, critical internal structure stress and wing surface pressure data collection. Wing deflections were also measured; flutter speeds were not determined experimentally although dynamic response was carefully observed while testing.

The morphing control system performed very well although, during operation at very high angles of attack, the actuator forces were less than required. This problem was due to an analytical error that could have been resolved if it had been identified during the design effort. This problem was not judged to be a major system problem.

Figure 25 shows TDT data for position measurements for two wing sweep angles as the wing re-positioned itself. The mechanism motion was smooth; the target position was achieved to within less than a degree and the wing stayed in the commanded position after it was moved.

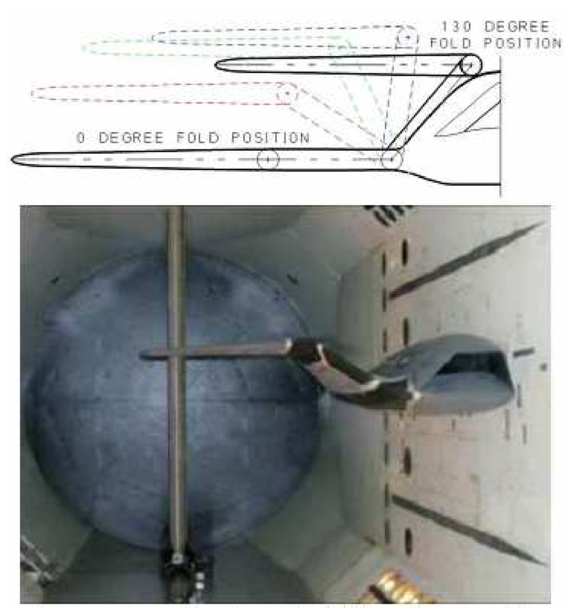


Figure 26 – Lockheed-Martin folding wing morphing design shown in the TDT

## Lockheed-Martin Aeronautics

Like the NextGen test model, the Lockheed-Martin folding wing design shown in Figure 26 (span 9 ft 7.4 in, length of 13 ft 7.6 in, total test article weight 1,450 lbs) was one of the heaviest ever tested in the TDT. The folding wing design incorporated: 1) ) light-weight thermo-polymer actuators that operated a leading edge flap used to close the gap between the fuselage and the wing in the fully-folded position The thermopolymer actuator was the first of its kind to be used for air vehicle applications and minimized part count and simplicity; 2) seamless elastomer skin/composite material folding joints (allowing 130 degree wing folding); and, 3) an integrated wing fold assembly to provide structural integrity through folding controlled by self-contained electric actuators for the wing fold mechanisms. This design uses wing folding in several positions to reduce wetted area and change sweep at critical points in the mission.

Figure 27 shows the progression from an initial UAV design with a payload of about 2000 pounds to the TDT model.

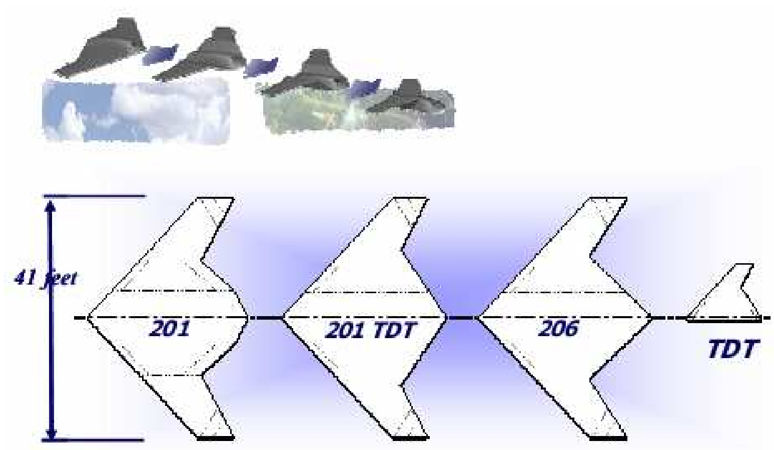

Figure 27 – Genealogy of TDT model development

Critical to this design are the active chordwise joints between wing panels. This joint design, shown in Figure 28, is complex. The joints use an embedded electric-motor-driven rotary actuator, a reinforced silicone skin cover that can stretch 50-100%, and a "knuckle joint" that is finger-like so that the joint can rotate, but still furnish a smooth exterior surface for the wing fold. In addition, the design uses a vacuum pump to draw the elastomeric skin into a cavity to prevent it from bunching up or otherwise interfering with the joint folding operation.

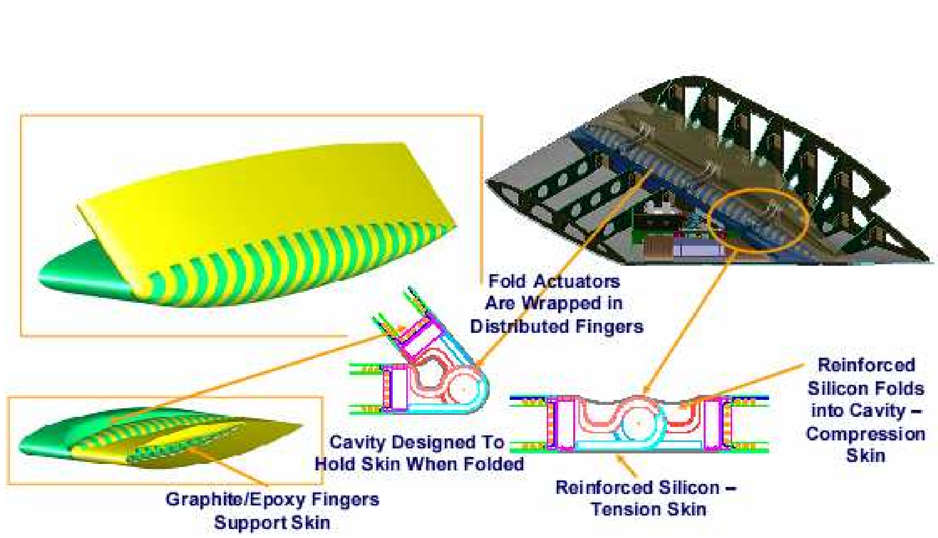

Figure 28 – Lockheed-Martin wing joint design

Pre-testing included dead-weight testing during which time the model was inverted; sand bags were loaded on the wing and electric motor operation to re-position the wing was demonstrated. GVT's were conducted with the model isolated on a stand in the laboratory and also with the model on the TDT mount system. During actual wind tunnel testing, a total of 161 TDT test runs were conducted.

Aeroelasticity plays a major role in the design effort. Recent studies have explored aeroelastic features of morphing aircraft[20,21] In Ref. 20, Dunn *et al.* demonstrated various efforts on aeroelastic analysis and optimization of the morphing wing configurations. In Ref. 21 Snyder *et al.* performed flutter analysis of a folding wing using hinge stiffness and wing folding angle as independent parameters. They found body-freedom flutter instability could occur with the folding wing configuration, but this was more a result of the fact that the configuration was a flying wing and was not unusual or unanticipated.

The Lockheed-Martin test program included active morphing tests during which the wind tunnel operator changed model angle of attack to keep a one-g load (2400 lbs.) on the wing while it morphed from the fully extended configuration to the fully folded configuration. Figure 29 shows the fold angle data for both the inner and outer fold lines as the wing control system moves the wing from its extended to its folded positions. This figure indicates that the movement is smooth and continuous.

## THE NEXT STEP-MORPHING FLIGHT CONTROL

Description of morphing for flight control.

## SUMMARY - AEROELASTIC CHALLENGES FOR STATE CHANGING AIRCRAFT

Summary of aeroelastic challenges for future shape changing aircraft.

From a systems viewpoint, the MAS effort demonstrated that MAS is a viable technical concept. This is not enough to insert innovative MAS concepts into the mainstream. Rogers[22] lists five different characteristics of an innovation that affect its adoption by technology users.

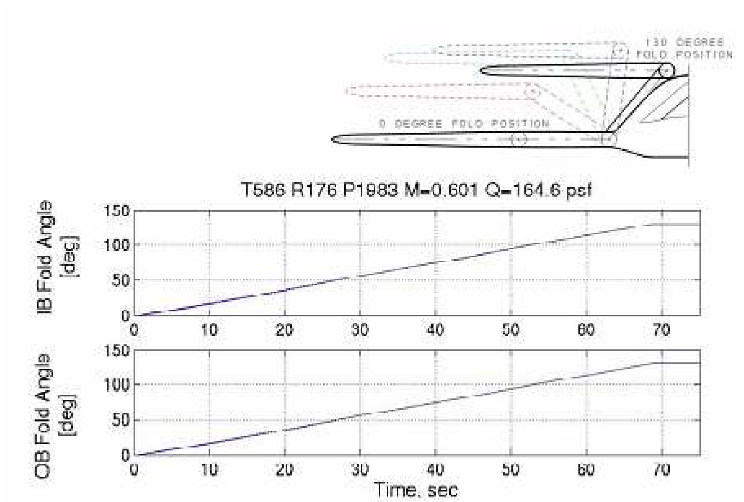


**Figure 29 – Lockheed-Martin wing fold angle test**

1) Relative advantage - the degree to which the innovation is superior to ideas it supersedes
2) Compatibility - the degree to which the innovation is consistent with existing values, past experiences and user needs
3) Complexity - the degree to which the innovation is easy to use
4) Trialability - the degree to which the innovation can be tried on a limited basis without commitment to full-scale, total operational change
5) Visibility - the degree to which the results of the use of the innovation are visible and communicated to users and other decision makers.

Still there are several needs related to aeroelasticity and design that must be addressed by researchers if this concept is to mature. These include:

# Acknowledgements

# References

1 E. Livne and T.A.Weisshaar, "Aeroelasticity of Nonconventional Airplane Configurations-Past and Future," Journal of Aircraft, Vol. 40, No. 6, November-December 2003, pp. 1047-1065.

2 A.R. Collar, “The first fifty years of aeroelasticity,” Aerospace, Vol. 5, Feb. 1978, pp. 12-20.

3 I.E. Garrick and W.H. Reed, “Historical Development of Aircraft Flutter,” AIAA 81-0491, Journal of Aircraft, Vol. 18, No. 11, Nov. 1981, pp. 897-912.

4 Defense Technology Objectives, DTO 71, DDR&E, Department of Defense, 2006

5 Clement Ader, Military Aviation (originally published 1909 as L'Aviation Militaire), Translated by Lee Kennet, Air University Press, Maxwell AFB, Alabama, July 2003.

6 Ibid.

7 Daniel P. Raymer, Aircraft Design: A Conceptual Approach, AIAA Education Series, 1992

8 Roy M. Braybrook, “The Annals of the Polymorph-a Short History of Variable Geometry,” Air International, Vol. 8, No. 3, March 1975, pp. 134-140

9 ibid

10 ibid

11 ibid

12 Peter Lert, “The fs-29, a telescoping wing sailplane,” Soaring, January 1976, pp. 21-27.

13 Fred Thomas, Fundamentals of Sailplane Design (translated by Judah Milgram), College Park Press, 1993

14 Robert W. Kress, “Variable Sweep Wing Design,” AIAA Paper 83-1051, 1983

15 Ray Whitford, Design for Air Combat, Jane’s Information Group, 1989, pp. 72

16 W.K.H. Kressner, The Boeing 2707 Supersonic Transport, Proceedings of the IEEE, Vol. 56, No. 4, April 1968, pp. 682-691.

17 Advanced Fighter Technology Integration, F-111 Mission Adaptive Wing, NASA CP-3055, 1990

18 William W. Gilbert, “Mission Adaptive Wing System for Tactical Aircraft,” Journal of Aircraft, Vol. 18, No. 7, July 1981, pp. 597-602.

19 John W. Smith, Wilton P. Lock and Gordon Payne, Variable Camber Systems Integration and Operational Performance of the AFTI/F-111 Mission Adaptive Wing, NASA Technical Memorandum 4370, 1992

20 Dunn, J., Horta, L., Ivanco, T., Piatak, D., Samareh, J., Scott, R, and Wieseman, C., “NASA Contributions to DARPA MAS Program,” Aerospace Flutter and Dynamics Council Meeting, May 12, 2004

21 Snyder, M, Frank, G., and Sanders, Brian, “Aeroelastic Analysis of a Morphing Z-Wing Configuration,” Snyder, M, Frank, and Sanders, G, Aerospace Flutter and Dynamics Council Meeting, May 12, 2004

22 E.M. Rogers, Diffusion of Innovations, Third Edition, Free Press, New York, 1983, p. 238