

Morphing Inflatable Wing Development for Compact Package Unmanned Aerial Vehicles

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Abstract

Many military and commercial applications for Unmanned Aerial Vehicles (UAVs) have been identified and numerous vehicles are under development. Many of these vehicles have a need to stow their wings and control surfaces into very small volumes to permit gun launch or packaging into aircraft mounted aerial drop assemblies. One technology that has shown promise in achieving this goal is the inflatable wing. Coincidentally, aircraft developers and researchers have identified a need for aircraft components that can morph to provide performance enhancements over traditional wing and tail assemblies, through the elimination of mechanical actuation system complexity and improved aerodynamics. The combination of the inflatable and morphing system technologies has lead to a unique approach for small UAV platforms with deployable, controllable wings that may also facilitate transition through multiple flight regimes.

Inflatable wings have been in existence for decades and have found application in manned aircraft, UAVs, munitions control surfaces, and Lighter Than Air (LTA) vehicles. Recent system design challenges have ushered advances in the areas of materials, manufacturing, and configuration that have advanced this technology into a practical form for near term application. Inflatable wings can be packed into volumes tens of times smaller than their deployed volume without damaging the structural integrity of the wing. Deployment can occur on the ground or in flight in less than one second depending on the size of the wing and the type of inflation system used.

The focus of this paper is to discuss efforts in reshaping, or morphing, the inflatable wing to provide roll control through wing warping, i.e. actuation of the aft end of the wing to achieve changes in section camber. Several approaches have been developed that lend themselves to camber control via locally altering the geometry of the wing. Apart from use as a stand-alone aerodynamic surface on a small UAV, the inflatable assemblies can also be used as an aspect ratio increasing device on a larger aircraft to enable a more radical change in wing configuration. This approach serves to improve system efficiencies across changing flight regimes, allowing transitions from high-speed target approach to low speed loitering.

Several actuation methods that are applicable to flexible structures have been studied and traded-off. Actuators with strong force generation capability (i.e. high blocked stress) can be added to inflatable structures to alter the length of the load bearing textile components of inflatable wings, thus altering overall shape. Performance requirements for such actuators were derived from a consideration of useful roll rate in a representative aircraft. Other requirements were also compiled and include such items as high frequency response, ability to be folded and packed, low mass, low power consumption, and high cycle life. Some of the actuator types considered include piezoelectric actuators, electro-active polymers, shape memory alloys, pneumatic chambers, nastic cells, and distributed motor-actuator assemblies.

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Examples of morphing inflatable wing configurations, actuator systems, and test data will be presented and discussed in this paper.

I. Introduction

Numerous UAVs are under development for varying military and commercial uses. One segment of the UAV market calls for the ability to package the wings and tail surfaces inside the fuselage to enable gun launch or compact carriage mounting for airdrop applications from a larger aircraft. This allows the user to launch a sensor package or munition to a target from many miles away using a large bore gun system, or airdrop small UAVs at a safe distance from the target. Once in the air and at a specified velocity, the UAV deploys its wings and tail, and then performs its mission. Similarly, it has been noted that for several portable UAV applications, highly robust aerodynamic surfaces that pack into small volumes are of importance. The highly damage resistant inflatable wing can facilitate human transport of small systems, transport using small vehicles, and various logistic advantages related to landings and quick turn-around.

Morphing of the wings of aircraft have been studied by numerous institutions¹⁻⁶. Much of the work in the field is centered on altering the airfoil shape to provide aerodynamic control or changes in the flight characteristics of the vehicle at varying velocities. More recently, morphing researchers have studied methods to radically alter the planform shape of a wing⁷. This has the potential to dramatically improve a vehicle's performance by allowing a single aircraft design to traverse through very different flight regimes. The inflatable wing can be used to address both needs. In the latter case, it can be used as a deployable tip extension of a conventional wing to increase its aspect ratio. A simple application would be a UAV that rapidly reaches its destination with short conventional wings, then deploys tip extensions at altitude to loiter. If used as a munition, it could drop its tips and dive on the target when needed. This approach employs non-retractable extensions. However, it is conceptually possible to construct a system with retractable inflatable wings to allow a continuous alteration in flight.

The approach to morphing whereby a wing of fixed planform undergoes geometric modifications to achieve aerodynamic control is the focus of this paper. One of the greatest challenges to overcome when morphing a conventional rigid wing is its inherent stiffness, or limited aeroelasticity. Researchers have studied methods of mechanically reducing the stiffness of conventional wings to allow them to be morphed^{5,8,9}. This adds complexity to the system and compromises wing mass and reliability. Alternatively, inflatable wings can be designed to be inherently less stiff in desired ways through materials modifications (weave, fiber selection, etc.) and cross-section design, without altering base structural performance. Therefore, it is possible to add actuators in targeted locations to warp the wing as the Wright brothers did on many of their aircraft, or to actuate the trailing edge in a smooth continuous form such that it acts as an aileron or flap. The importance of the smooth continuous shape has been noted in several studies as an advantage over conventional flaps because of improved aerodynamic performance^{2,3,5,6}. An approach such as this will enhance flow attachment thus improving aerodynamic efficiency. This translates to reduced fuel consumption over the duration of the flight – a critical need for UAV operation.

ILC has participated in several previous and ongoing studies of morphing inflatable wings. Attempts have been made to focus each of these studies in slightly different directions to obtain a broad understanding of the technology. The guiding motivation for the work has been to develop a deployable UAV inflatable wing that will provide aerodynamic control via small embedded actuators. This approach has the potential to be of lower mass in comparison to mechanical technologies, especially if integrated multi-functional materials such as electronic textiles or membranes can be applied. Electronic textiles and membranes are an emerging class of materials that combine electrical components directly into the base materials. These materials can be made to perform various functions such as changing shape via constriction, producing and storing power, acting as sensors or embedded antennas, or as microcircuits. As a precursor to fully integrated actuators, research involving PZT (lead zirconium titanate) actuators is being conducted by California State University San Bernardino in conjunction with NASA Dryden Flight Research Center and ILC Dover. Work is in process to assess the effectiveness of a patch actuator mounted directly to an inflatable wing. The actuator is sized roughly to be 2-3% of wing area. Furthermore, research is underway under the auspices of the University of Kentucky's Mechanical Engineering Department and ILC Dover involving SMA (shape memory alloy) deformation cables to facilitate in-flight demonstration of inflatable wings.

The majority of the work presented in this paper was performed under subcontract to Swales Aerospace under an Indefinite Delivery Indefinite Quantity contract, with funding provided by NASA Langley Research Center. Under this contract, ILC Dover pursued the development of several morphing inflatable wing concepts, structural analysis of the assemblies, and manufacturing and test of prototypes. The dynamic analysis was conducted by Swales Aerospace. NASA LaRC provided program oversight and technical guidance, and conducted CFD analysis.

II. Background

Inflatable and rigidizable wings have been under development for some time and have been developed for several UAV applications¹⁰. ILC Dover demonstrated a 5-foot wingspan inflatable flying wing (the Apteron) in the late 1970s with great success. Several development programs for UAVs with inflatable wings have been conducted over the past few years, and inflatable wings have recently been manufactured by ILC Dover and flight-tested by the University of Kentucky and the University of Maryland in 2003 and 2004 (Fig. 1). Flight testing of morphing wings is also planned at these locations.

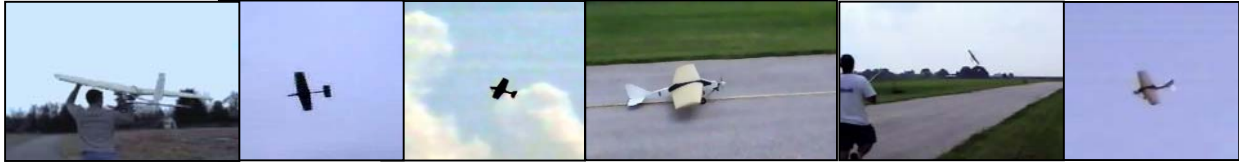


Figure 1: Inflatable Wing Flight Testing

The strength and stiffness of the inflatable wing are dictated by the type of material used, the cross-section design of the wing, and the internal pressure. It is favorable to reduce the internal pressure to as low a value as possible to reduce risk, reduce mass of the inflation system and structure, and reduce leakage rates. Optimization of these variables is possible through use of a design that is comprised of a series of fabric spars that run span wise, and are attached to an upper and lower fabric restraint¹⁰. A polymeric bladder is positioned within the assembly to contain the inflation gas. This approach maximizes the area moment of inertia of the cross section; thus minimizing the inflation pressure required to prevent buckling.

The surface of the inflated structure has a bumpy appearance, as inflatable structures approximate the shape of a cylinder or sphere upon inflation (Fig. 2). In this case, the wing appears to be a series of intersecting cylinders. This geometry has a positive effect on wing performance at low Reynolds numbers ($< 500,000$) and helps maintain flow attachment. However, for higher Reynolds number applications, a skin is added to the surface of the airfoil. A smooth fabric or film is selected to reduce aerodynamic drag. The skin is attached and indexed to the underlying structural fabric restraint such that it bridges the bumps and closely approximates the shape of the nominal airfoil section. The skin and underlying structure are compliant such that they pose no obstacle to folding, packing, and deployment of the wing. Additionally the skin exhibits a degree of porosity to prevent the formation of pressure variations between the skin and restraint, thus eliminating the potential for displacement of the skin from the prescribed airfoil shape. Both the wing restraint and the wing skin can be used as locations for installing morphing actuators. Attaching at the restraint generally supports localized change in airfoil profile, while the skin facilitates distribution of actuation forces across the wing.

One of the more notable features of an inflatable wing is its durability. The materials are robust and can be packed and deployed numerous times as required. The use of the inflatable precludes damage in shipping, handling, flight, and landing, through the impact resiliency of the materials and natural impact absorption capabilities of an inflated structure. Similarly, the wing can recover shape in flight if the load limit is exceeded and the wing buckles. The use of low dielectric materials also reduces the radar cross section of the vehicle.

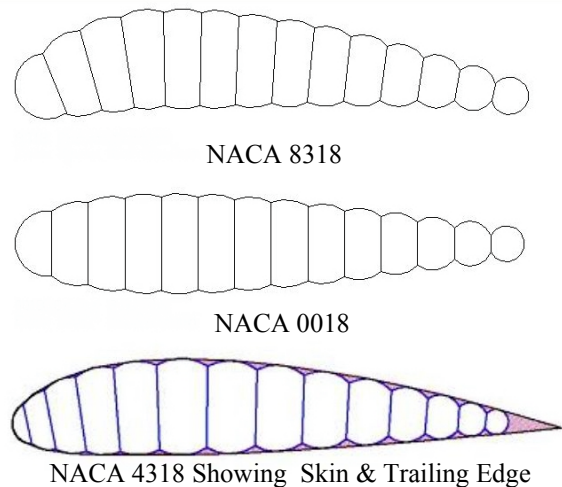


Figure 2: Inflatable wing profile

III. Baseline Wing Configuration

An inflatable wing design representative of those used by ILC Dover on recent UAV applications was chosen as the platform for the development of a morphing prototype wing (Fig. 3). Relevant specifications for this wing are: NACA 4318 nominal airfoil, wing area of 7.2 ft², 6 ft span, 17 in root chord, aspect ratio of 5.4. The wings were

designed for use on a 100 lb vehicle operating at a nominal cruise speed of 90 knots. Worst case loading condition is a very modest 2 G's.



Figure 3: Baseline Inflatable Wing Configuration

The material used in the manufacture of the wings is Vectran, a high strength liquid crystal polymer with excellent performance properties for UAV wings. The design of the fabric and seams is dictated by the wing's inflation pressure, which is driven by vehicle weight and the maximum accelerations the vehicle will undergo.

The development of a morphing capability for the wing depends on an understanding of the wing's internal structural and inflation loads. The morphing elements must be added in a manner that minimizes any reduction in fiber pre-load caused by the wing's internal inflation pressure, otherwise the structural stiffness of the wing may be compromised. The loads in the wing were studied in detail, but a simplified analysis is presented here to demonstrate the approach and the general loads that were considered in selecting actuation systems. The hoop stress in the cylindrical bumps is governed by the expression:

$$\sigma = P \cdot r$$

where: σ = Skin stress (hoop direction)
P = Internal pressure
r = Radius of curvature

Since the radius of curvature of the bumps decreases as one moves from the maximum wing thickness toward the trailing edge, the skin stress correspondingly drops. Thus, actuators that deform the wing by overcoming fabric hoop stress will have reduced demands placed on them if they are located nearer the trailing edge. A full analysis of the inflatable wing at the operating conditions noted above shows that a nominal inflation pressure of 48 psig is required to prevent the wing from buckling under flight loads. At this inflation pressure, the hoop stress in the region of wing near the tip varies from 52 lb/in in the largest cell (~1/3 chord), to 14 lb/in in the smallest cell (trailing edge). (Note that stress in a thin shell structure such as an inflatable is typically expressed in lb/in. Stress may be calculated in a traditional manner, but then both sides of the equation are multiplied by the fabric thickness, removing thickness from the calculation, yielding stress expressed in lb/in.)

The derived stresses were used as the basis of development for each of the morphing wing actuation systems.

IV. Morphing Requirements

In order to determine an optimal system configuration based on a given type of actuator, a set of requirements was adopted to govern a configuration trade study:

- Maintains tensile load in fibers (critical to design of an inflatable)
- Distributed usage over entire wing desirable for scaling and adaptability
- Low weight: < 5 lb per half span target, including morphing system
- Low packed volume: < 150 in³ for the total system
- Able to be folded, packed efficiently, and deployed multiple times (>50)
- Can be integrated / repaired after wing manufacture
- Fail safe with redundancy considerations
- Maintains aerodynamics, i.e. the devices which cause shape alteration do not disturb the airflow
- Simple to manufacture - minimize specialty tooling and machine needs – low cost

- Low abrasion potential between actuators and wing restraint

Similarly, a set of criteria was adopted to govern a set of trade studies on the actuation system:

- Low power consumption
- Rapid reaction speed (>1Hz)
- Low weight (<10% of wing weight)
- Able to be folded, packed efficiently, and deployed multiple times (>50)
- High blocked stress
- Fail safe with redundancy considerations where possible
- Simple and inexpensive to integrate
- Distributed usage over entire wing desirable for scaling and adaptability
- Maintain position over time i.e. minimize creep and hysteresis
- Low materials and integration cost
- Available power source - existing vehicle batteries/system often provide low voltage DC

Of particular interest in the development of the system level requirements was the identification of a desirable roll rate that could be used as a design target. From a survey of typical aircraft configurations, roll rates among designs were compared in an effort to identify average and bounding values. A roll rate of 45 degrees per second, on par with a Cessna 152, was determined to be a reasonable design goal. A first order inertia model was constructed, modeling the inflatable wings attached to a UAV-representative fuselage with accompanying tail structure from a previous application. The model made use of the mass properties of the wings, fuselage, and tail to determine the mass moment of inertia about the configuration's roll axis. This value was inserted into Newton's second law in the form:

$$\tau = I * \alpha$$

Where: τ represents the roll torque (ft-lb)
 I is the mass moment of inertia (slug-ft²)
 α is the angular acceleration of the vehicle about the roll axis (rad/sec²)

For simplicity of calculation, a constant angular acceleration was assumed, the magnitude of which would be sufficient to rotate the vehicle from rest to 45 degrees in 1 second. Obviously, if this angular acceleration continued to be present, the roll rate would continue to rise, but for the purposes of the study, this simplified approach was deemed appropriate. Thus, substituting $\theta = .785$ rad (45 deg), and $t = 1$ sec into a formula for rotary motion with constant acceleration:

$$\alpha = 2*\theta/t^2$$

yields:

$$\alpha = 1.57 \text{ rad/sec}^2$$

Based on a calculated inertia for the vehicle of 0.42 slug-ft² it was determined that the system would need to generate a roll moment of 0.66 ft-lb to rotate from rest through 45 degrees in one second. A comparison of this roll moment requirement to the capabilities of the developed system will be presented later in this paper.

V. Concept Development & Trade Studies

Numerous concepts were developed that leveraged the attributes of the inflatable wing to create a morphing structure. The generation of ideas was separated into two areas - the configuration of the wing and its methodology in morphing, and the actuator technology. A trade study of each area was conducted to identify the top options and then the results of both areas were combined to formulate complete solutions. The concepts were evaluated against

the requirements noted above, and weighting factors were assigned for each of the requirements to prioritize their importance.

The configuration options that were developed are noted below, and the items that were selected for further evaluation are presented in detail later in the paper. The configuration options identified include:

- *Nastic patches on bumps (pneumatic)*
- *Skin constriction*
- *Restraint bump flattening*
- *Trailing edge deforming plates*
- *Fan patches & cables (foreshortening)*
- Restraint bump constriction
- Capstan tensioning at junctions (internal)
- Capstan tensioning at junctions (under skin)
- Pneumatic pylons (constricting braid)
- Nastic patches on bumps (electro-mech)
- Inflatable torque tube
- Large patch actuator for global bending
- X-spars with variable pressures
- H spars with an elastomeric restraint

Italicized items indicate the options identified for further study. Details of the leading options are presented later in the paper. Various permutations were also considered but not noted here. The items selected for further study were not only selected for their anticipated performance, but also because they were collectively different enough to provide a wide range of understanding in the overall study.

The driving factors which lead to the selection of the leading concepts highlight the strengths and weaknesses of each concept. The nastic patches integrate well with inflatable structures and offer a simple approach to shape change, but may be limited by response time. The skin constriction method integrates nicely and provides a mechanical force that is simple to apply and control, but is limited by actuator capability. The restraint bump flattening method integrates well and is simple to control, but is limited by actuator availability and packing volume. The trailing edge plates that deform assist with creating a sharp trailing edge and enable a variety of actuator options, but may be more susceptible to deployment damage. The use of fan patches and constriction cables is attractive in its simplicity and potential large force generation, but must be controlled regarding abrasion, restraint unloading, and local deformations at fan patches.

The same approach was used to identify actuation technologies and select the leading candidates. The technologies considered include:

- *Piezoelectric / Piezoceramic*
- *Pneumatic*
- *Electro-Active Polymer*
- *Shape Memory Alloy*
- Piezoelectric Motor
- Electromagnets
- Electric Motor
- Hydraulic
- Shape Memory Polymer

The items that are italicized were the options identified for further study. The piezoelectric/piezoceramic actuators provide high blocked stress with acceptable strain, but are susceptible to handling issues. Pneumatic devices offer the potential for high force generation and large deflections, but are slow in response rate because of fluid transfer issues. Electro-Active Polymers integrate well, but are limited by the current capabilities of the

material regarding blocked stress and strain. Shape memory alloys are simple to apply and good in compact applications but are limited in response time. Advances are being made in the electroactive materials that will enhance their applicability at they mature.

VI. Nastic Structures

Nastic structures are biomimetic devices whereby materials are activated to generate large strains while still performing a structural function¹¹. The basic concept is simple. A series of parallel tubes into which a fluid of varying pressure may be pumped is arranged adjacent to one another. As fluid is pumped into the cells, they transition from a flat to a circular cross section. This both foreshortens the cells and provides a force generating capability, with increasing pressure resulting in higher forces. However, there is a limit to the useful force that can be developed, because the angle of the cell wall at the point where it terminates increases to perpendicular as the cell approaches a circular section. This causes a reduction in the resultant force that can be transmitted (Fig. 4).

Examples of nastic structures include numerous organic plants, which are able to modulate the internal pressure of microscopic fluid filled cells to generate non-symmetric strains over the cross section of their stems¹¹. This provides them with the capability of movement, allowing them to move toward and track a light source. This effect can also occur rapidly in some plant structures as demonstrated by the Venus Fly Trap.

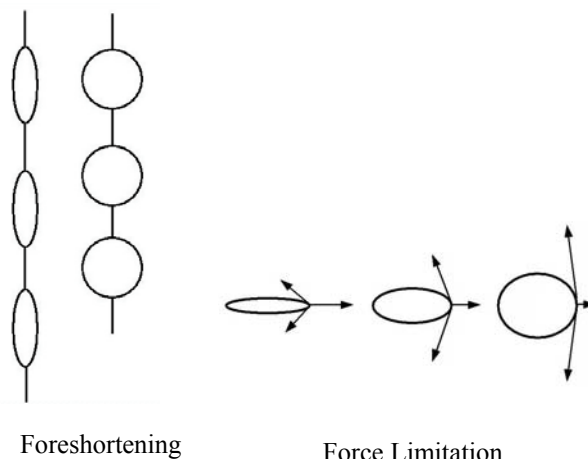


Figure 4: Nastic Concepts

As applied to the morphing of an inflatable wing, a series of cylindrical inflatable tubes can be oriented span wise along the wing, pneumatically isolated from the inflation volume of the wing. A series of such tubes can be located on both the upper and lower surfaces of the wing. By independently varying the pressure within the tubes in the upper and lower surface, the airfoil trailing edge can be made to constrict and bend in the direction of the inflated cells, as seen in Fig. 5.

The force requirements for this method of actuation are based on the skin stress of the un-inflated nastic cells, which is linearly proportional to wing inflation pressure. Inflating the nastic cells such that they overcome this skin stress will enable geometric change and thus morphing.

Developmental testing was performed with a nastic cell mockup to assess the concept's viability as a morphing technology and to better understand methods of implementation. A test article was fabricated with cell diameters of 0.84" and installed in an Instron tensile test machine (Fig. 6). When inflated to pressures of 50, 100, and 135 psig, tensile skin stresses of 134, 188, and 212 lb/in respectively were developed, as measured according to an ASTM D5034-95 grab tensile test. These force values compare favorably with the skin stress due to wing inflation pressure calculated earlier, which range from 14 to 52 lb/in.

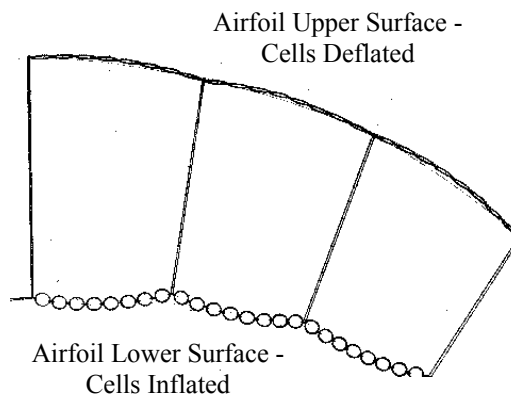


Figure 5: Nastic Morphing Concept

While these results looked promising, spreadsheet calculations indicate that a set of nastic tubes suitably sized for the inflatable wing test article would have difficulty generating the tensile force necessary to overcome the skin stress due to wing inflation pressure. There was also a question as to whether enough displacement would be available, given the small number of tubes that could be placed on a wing. Further, calculation and observation indicate that the approach would suffer from slow reaction times, and would require more support hardware than mass limitations would permit. Thus, the nastic concept was not pursued beyond the test article.

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If the nastic cells were implemented on a wing that was large enough to allow the use of a reasonable number of tubes, and if the internal inflation pressure within that wing was not excessive, then the approach may have potential

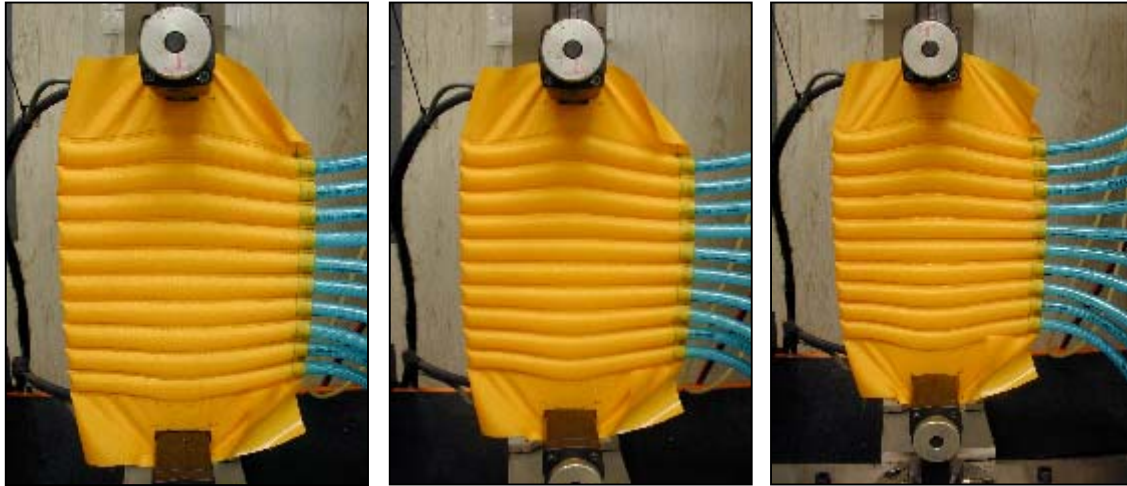


Figure 6: Nastic Tensile Test at 20, 50 and 100 psig (left to right)

for longer term shape change applications such as configuration changes between take off and landing, or between cruise and dash. In this case, it is estimated that the mass increase due to the nastics would not be excessive, perhaps in the neighborhood of 5 – 10 %. However, the associated support hardware could add significantly more – items such as pumps, proportional control valves, etc.

VII. Bump Flattening

Morphing of an inflatable wing can be achieved using a technique called “bump flattening”, in which actuators are applied directly to the wing restraint. A piezoelectric actuator is bonded first to a rigid substrate, and then to the wing restraint fabric. When energized, a force is generated perpendicular to the plane of the actuator, resulting in a flattening of the individual bumps caused by the wing spar spacing. By flattening individual bumps in series, a net increase in run length is generated, resulting in deflection of the wing’s trailing edge (Fig. 7).

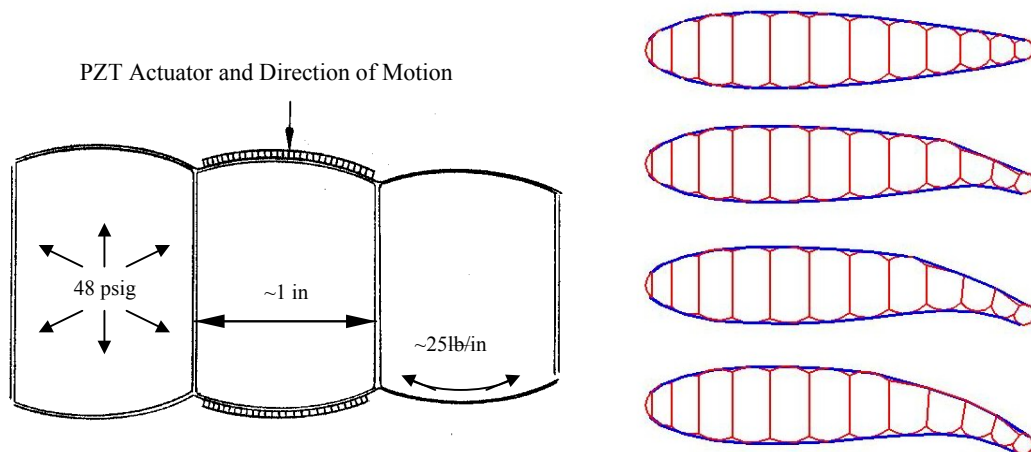


Figure 7: Bump Flattening Concept

This approach requires the actuator to overcome the wing’s internal inflation pressure. It must generate an out of plane force equal to the inflation pressure multiplied by the actuated area. A prototype was assembled to evaluate the approach. The actuator selected was a commercial off the shelf Macro Fiber Composite actuator from Smart Material, measuring 4.3” x 1.5”, and bonded to a steel plate, 0.010” thick. A single actuator was able to span multiple bumps, so it was deformed to follow the contour of the wing (Fig. 8). Based on the area of an actuator over a single bump, a force of approximately 72 lbs was required to overcome internal inflation pressure. It was found that the actuator was unable to develop the necessary force. Similar actuators available from FACE were also considered in the application, but yielded the same result.

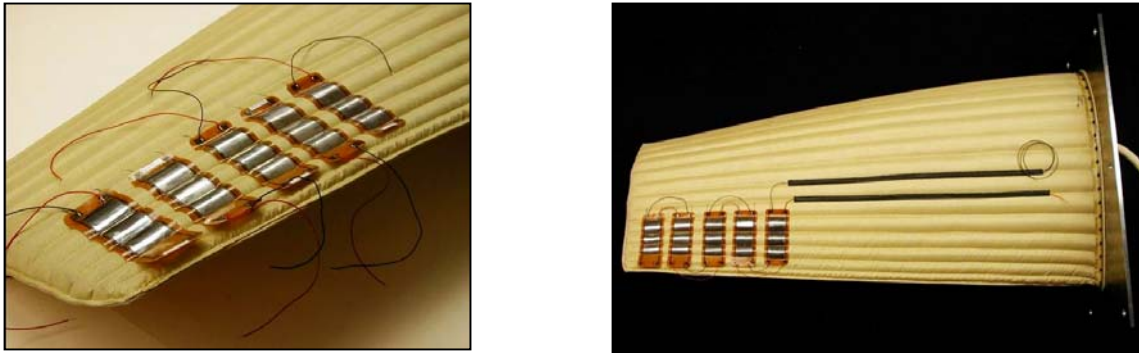


Figure 8: Bump Flattening Prototype

Despite unsatisfactory results in the current configuration, bump flattening has not been ruled out as a viable morphing technology. Actuator optimization, including stacking, use of bimorphs, and plate refinement, were not conducted within the study, and the technology continues to mature. The approach appears valid for scaled cases where the inflation and applied loads are more manageable. The mass of such a system, should it prove viable, is expected to be quite low – on the order of 5% of the mass of the wing.

VIII. Trailing Edge Deflection

One of the most promising morphing configurations for near term application was found to be a series of trailing edge actuation devices. This approach modifies a baseline inflatable wing configuration with PZT actuators that flex the trailing edge of the wing. Unlike ailerons however, the actuators reside under the wing skin, presenting an uninterrupted surface to the air stream.

The actuators were considered in both unimorph and bimorph configurations. In the bimorph configuration, two MFC actuators from Smart Material were bonded to a metallic substrate. The actuators expand or contract in response to the application of a positive or negative voltage¹². By applying opposite polarity voltages to the upper and lower actuator, the substrate is caused to flex (Fig. 9).

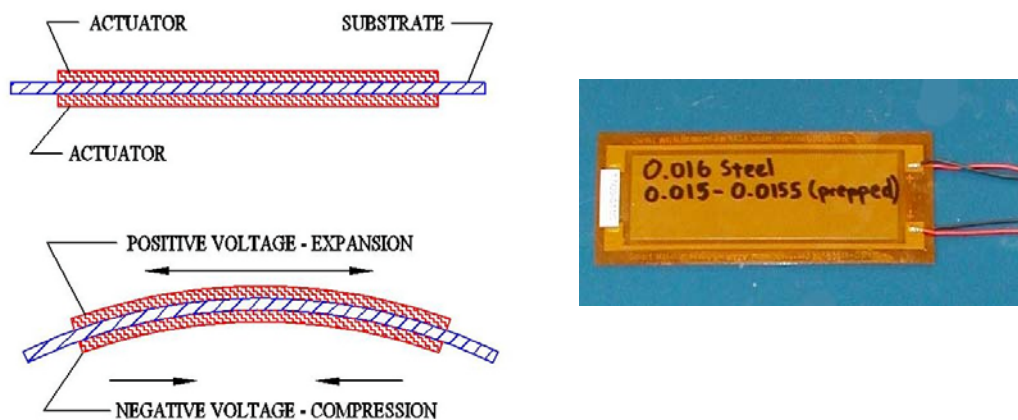


Figure 9: Trailing Edge Actuator Concept of Operations & Sample Unit

Investigations were conducted to assess the performance of several actuator configurations, in addition to the bimorph configuration just discussed. For each configuration, the actuator was set up as a cantilever, with one end clamped to a tabletop, and the other end free to move. The actuators can operate with a range of voltages from -500 VDC to + 1500 VDC. For the case of the bimorph configuration, a single power supply was used with a voltage dividing circuit arranged to provide a maximum of +1500 VDC to one actuator while applying -500 VDC to the other. Due to the nature of the actuators, current draw is negligible. Voltage was applied to the actuator with the

polarity such that the free end of the actuator curled up from the tabletop. With the actuator so energized, a gauge was used to measure the force required push the free end flat to the table (back to its de-energized state). The displacement between energized and de-energized states was also measured. Several actuator configurations were assessed: unimorph (single actuator bonded to substrate), bimorph (two actuators as discussed above), in addition to varying the material and thickness of the substrate. Experimental results are shown in Table 1. It was observed that there was a trade-off between force and displacement. The bimorph configuration with a .0145" aluminum substrate was selected for integration to a wing, as it was judged to provide the best blend of force and displacement. It was found that this configuration resulted in an effective control surface deflection of 3 degrees at maximum actuation.

Table 1: MFC Actuator Test Results

Configuration	Applied Voltage (Volts)	Total Displacement (inches)	Force to Flatten (pounds)
Unimorph 0.015" Steel Substrate	+ 500	0.063	
	+ 1000	0.125	0.50
	+ 1500	0.188	0.90
Unimorph 0.0145" Alum Substrate	+ 500	0.141	0.30
	+ 1000	0.266	0.50
	+ 1500	0.391	0.60
Unimorph 0.0195" Alum Substrate	+ 500	0.109	0.20
	+ 1000	0.188	0.40
	+ 1500	0.281	0.65
Bimorph 0.015" Steel Substrate	+1500/-500 simultaneous	0.125	1.60
Bimorph 0.0145" Alum Substrate	+1500/-500 simultaneous	0.188	1.20

The actuators are attached to the upper surface of the wing, extending rearward and terminating at the nominal trailing edge location (Fig. 10). The actuators are arranged with span wise gaps to facilitate folding and packing of the wing. Upon application of a voltage, the actuators curve upward or downward, depending on the polarity of voltage applied. When the voltage is removed, the actuator returns to its nominal un-deflected position. On the development unit, an elastic fabric was stretched from the trailing edge of the upper wing surface to the trailing edge of the lower wing surface to enclose the actuators, suggesting how the actuators could be covered by a skin. Together, the actuator and elastic fabric provide a sharp trailing edge to the wing. An alternate configuration is possible, with an actuator

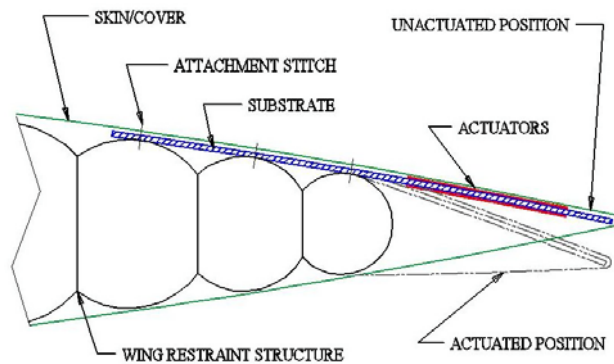


Figure 10: Trailing Edge Configuration

attached to both the top and bottom surface, instead of just the top. This could potentially increase the amount of force available for deflection.

A prototype assembly was manufactured and bench tested (Fig. 11).



Figure 11 – Trailing Edge Deflection Morphing Wing Prototype

During actuation under cruise conditions, there are a number of loads exerted on both the actuator bimorph and the assembly attachment point to the inflatable wing. The elastic fabric loads the bimorph, imparting a downward bending moment at the wing attachment point. When actuated, the curved bimorph will experience aerodynamic loading that induces an upward bending moment estimated at 0.3 inch pound at the same point. The elastic fabric can be tensioned such that it will assist in combating aerodynamic loads during actuation. The relative stiffness of the attachment point to the wing and the bimorph will determine if the actuator assembly will tend to flatten out, or maintain shape and transmit the load directly to the attachment point. The fabric must be tensioned such that it resists flutter and transient deflections due to aerodynamic buffeting, but does not create so much force as to yield the bimorph substrate.

An analysis was conducted to assess the design's ability to satisfy performance requirements. Measurements of actuator deflection were used to calculate the lift increase that could be expected during trailing edge deflection¹³. DesignFOIL, a commercial airfoil design and analysis software tool, was used to calculate the difference in lift per unit span between the actuated and un-actuated states. The results are shown in Fig. 12.

The net wing lift changes from 96 lb to 108 lb when the trailing edge is actuated. In addition to an increase in lift, there is an outboard shift in span wise center of pressure. The location of the center of pressure with respect to the wing root shifts from 15.3 in when un-actuated, to 16.8 in when actuated - a shift in moment arm of 1.5 in. If one half span is actuated, and the other is not, there will be a 28.8 ft-lb roll moment generated at the maximum actuation of 3 degrees. This is well in excess of the target value of 0.66 ft-lb identified above.

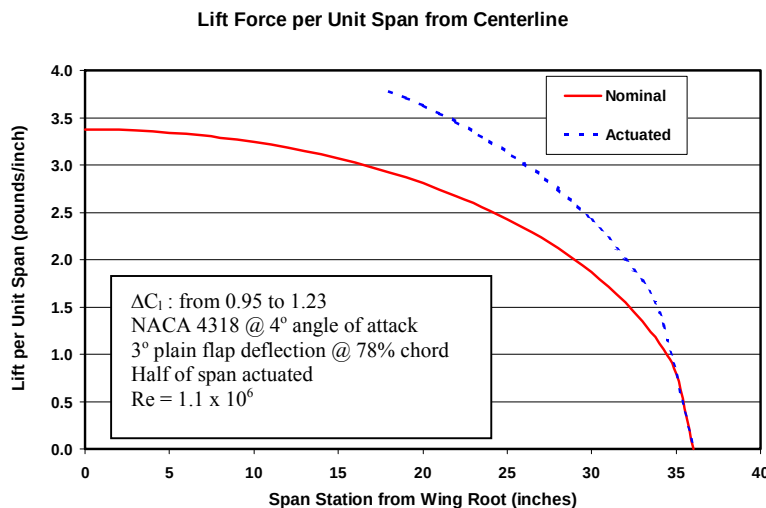


Figure 12: Calculated Lift Force per Unit Span

IX. Summary

The morphing studies conducted developed considerable data for the design of a morphing inflatable wing. As a result of these research and development efforts, progress was made in several new technology areas including the advancement of nastic structures technology and the successful use of piezoelectric actuators to form a controllable trailing edge. The concepts developed are leading toward the manufacture of inflatable wings for small UAVs with embedded aerodynamic control, and may also have application for aspect ratio morphing of larger UAVs.

An intriguing approach that may have future application potential was the incorporation of nastics technology. Although the scope of the funded development effort did not allow prolonged study of the technology, advancements were made in the understanding of the capabilities of the actuators, with respect to force and displacement capacity and inflation pressures required. Further advancement of this technology may yield breakthroughs where space constraints and available packing volumes limit the application of conventional actuation technologies.

The flattening of restraint bumps on an inflated wing structure presented several challenges, not the least of which was the force required to overcome the wing skin stress resulting from high internal wing pressures. During the course of development and testing, it was found that the current generation of piezoelectric actuators could not generate enough force to overcome the internal pressure of the inflated wing. Although the configuration studied was not amenable to the use of these actuators, they may be appropriate once the actuator technology has advanced to the point that it can generate significantly more force and displacement.

The trailing edge piezo actuator was determined to be a useful method of achieving control capability with a rapid response rate. It was found that an adequate roll moment could be produced by a control surface that does not have a definable hinge point or airfoil discontinuity. This is a significant advancement in inflatable UAV wing design.

As the development of robust morphing inflatable wing technology progresses, and more advanced actuator technologies are investigated and applied, the morphing inflatable wing will be an attractive option for UAV applications. Development of an inflatable wing morphing capability builds upon a foundation of inflatable wing design that has demonstrated that wings can be packed into a small volume and rapidly deployed in both ground-based and airborne launch modes. The ability of the deployed wings to incorporate control surfaces will bring the technology to a new level, eliminating the need for large area tail control surfaces. This technology is enabling for both military and non-military applications. For military purposes, inflatable wing based UAVs can be designed for gun launch, ground launch or airborne launch modes supporting both reconnaissance and munitions delivery missions. In the homeland defense arena, UAVs with fully functional, morphing inflatable wings can be used in a variety of applications from border patrol to surveillance and inspection. Finally, broad commercial applications are possible and range from airborne observation of crops to inspection of pipelines and power lines. In these instances, the ability to fly, land, and rapidly repack and relocate the UAV to a new launch location is key to the success of the mission, and is made possible in part by a morphing inflatable wing.

Although morphing inflatable wing technology is still in its infancy, ILC Dover continues to explore this enabling technology through several current and planned development efforts.

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