Design and application of compliant mechanisms for morphing aircraft structures

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ABSTRACT

Morphing aircraft structures can significantly enhance air vehicle performance. This paper highlights ongoing work to design novel compliant mechanisms that efficiently morph aircraft structures in order to exploit aerodynamic benefits. Computational tools are being developed to design structures that deform into specified shapes given simple actuator inputs. In addition, these synthesis methods seek to optimize the stiffness of the structure to minimize actuator effort and maximize the stiffness with respect to the environment (external loading). These tools have been used to study two different types of morphing systems: (i) variable geometry wings and (ii) high-frequency vortex generators for active flow control. Several case studies are presented which highlight the design approach and computational and experimental results of these morphing aircraft systems.

Keywords: Aircraft Morphing, Active Flow Control, Structural Optimization, Compliant Mechanism

1. INTRODUCTION

A compliant mechanism is a class of mechanism that relies on elastic deformation of its constituent elements to transmit motion and/or force. These monolithic structures, an example is shown in Figure 1, are in fact mechanisms without any joints – neither conventional hinges nor flexural hinges. Many practical benefits can be realized by exploiting compliance in engineering design. These include: reduced complexity, zero backlash and wear, sub-micron accuracy, and embedded actuation/sensing[1]. Mechanisms that possess distributed compliance, as opposed to lumped compliance, are much more fatigue resistant and easier to manufacture. Distributed compliant mechanisms derive their flexibility due to the topology and shape of the material continuum rather than concentrated flexion at few regions such as flexural hinges. Several computational approaches have been developed to design compliant mechanisms for desired force-displacement characteristics[2, 3] and more recently for generalized shape change. In addition, these novel mechanisms can be readily integrated with both conventional and unconventional (smart materials) actuation schemes[4].

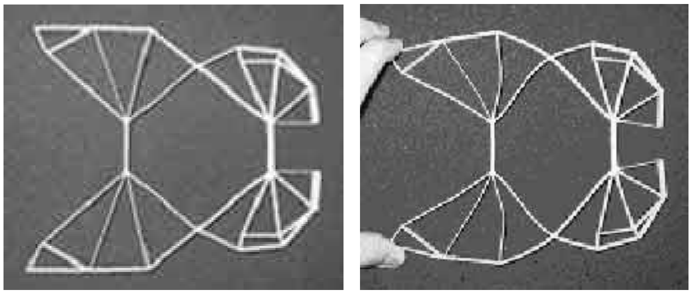

Figure 1: A structurally optimized compliant gripper illustrating distributed compliance

Because of these advantages, properly designed compliant mechanisms are well suited for shape morphing applications such as variable geometry leading and trailing edge surfaces, engine inlets, and other aircraft components. Their unitized construction makes their manufacture relatively simple, eliminating most complex assembly operations. And in many

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cases, the absence of joints can offer additional weight savings. Furthermore, problems due to wear, backlash and lubrication are eliminated. Compliant mechanisms can be designed for desired stiffness with a variety of materials including titanium, aluminum, steel, nitinol and composites. Two general applications for compliant mechanism technologies are highlighted in this paper: (i) variable geometry wings – specifically for leading and trailing edge flaps and (ii) high-frequency vortex generators for active flow control.

1.1 Variable geometry wings

It is a well-known fact that changing the shape of an airfoil over the course of a mission can offer significant benefits in terms of reduced drag, enhanced lift, and reduced radar cross-section. In the mid 1980s, Air Force Research Labs (AFRL) at the Wright Patterson Air Force Base (WPAFB) tested a modified F-111 aircraft, called Mission Adaptive Wing (MAW). Using conventional rigid-link mechanisms combined with fiberglass flex-panels, the concept proved its aerodynamic superiority over conventional leading and trailing edge flaps[5]. Figure 2 illustrates the mechanical systems that were developed to change the shape of the upper leading and trailing edge surfaces of the F-111 wing. Unfortunately, drawbacks inherent in the design did not offset aerodynamic benefits. Specifically, increases in weight, complexity, space, and mechanism backlash halted the program from further development. Since the MAW, other concepts have been proposed by researchers in smart materials and smart structures; however, scalability and survivability of these approaches has always been an issue.

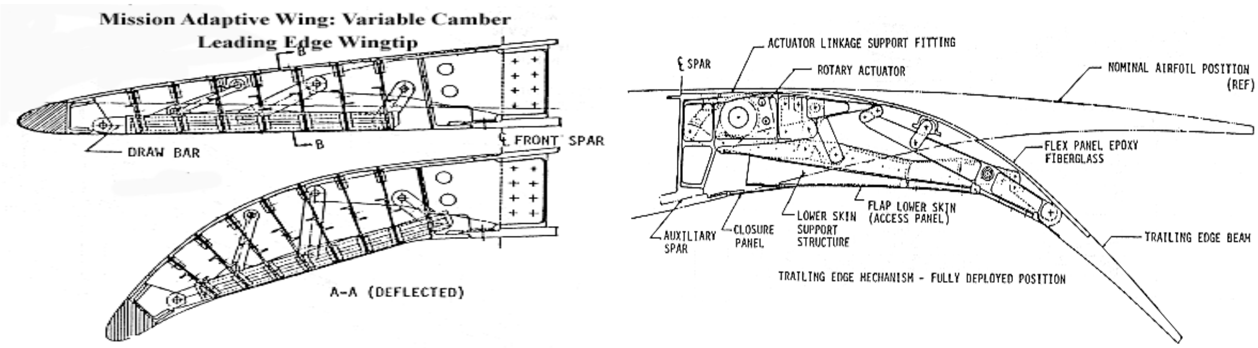


Figure 2: Leading and trailing edge mechanisms developed for the F-111 Mission Adaptive Wing program

Starting in 1998, compliant mechanism technology was first applied to the wing morphing problem. Working with funding from the AFRL Air Vehicle Directorate, a compliant variable camber wing leading edge (a 3-foot NACA63418 profile embedded with compliant mechanisms) was designed, fabricated, and tested[6]. The leading edge compliant mechanism is designed to withstand the external air-loads while producing a 0 to 6 degree change in camber. Wind tunnel test results showed a 51% increase in lift-to-drag ratio and a 25% increase in the lift coefficient for the 6-deg. Leading edge camber change (Figure 3). Since the phase I study, a phase II contract has been awarded to study the scalability, weight, and power requirements of compliant mechanisms for full-scale shape morphing applications. Ongoing results of this study suggest that compliant mechanisms are in fact a scalable solution for full scale aircraft. Additionally, research suggests that they can be competitive in terms of weight and power consumption relative to conventional hinged flap systems.

The primary challenge for compliant shape morphing systems is to create an efficient structure that can distribute local actuation power to the surface of the airfoil to produce a specified shape change. This system must provide the appropriate shape control over the surface while meeting stiffness, power, weight, packaging, and survivability constraints. On going work at FlexSys Inc. is focused on developing computational design tools to speed design of such structures, as well as the knowledge base for materials, actuation systems, adhesives, etc. to fabricate and test these novel systems. Research for developing successful variable geometry leading edge and trailing edge systems, must address many criteria including the required aerodynamic shapes, the required stiffness and dynamic response, and the weight and power required to actuate the control surface. Using FlexSys Inc. proprietary *Continuous Shape Generation* (CSG) software, the authors have been able to design compliant structures to produce morphing wing structures that can meet relevant design constraints such as stress, stability (buckling), dynamic behavior, stiffness, etc.

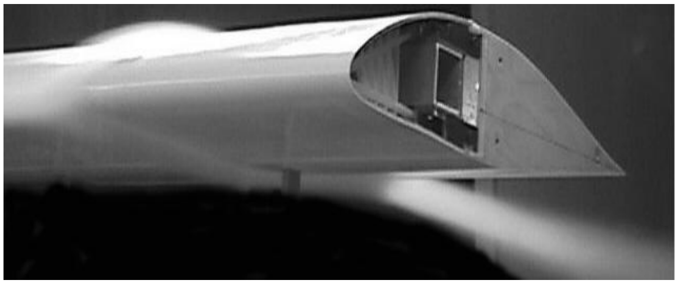
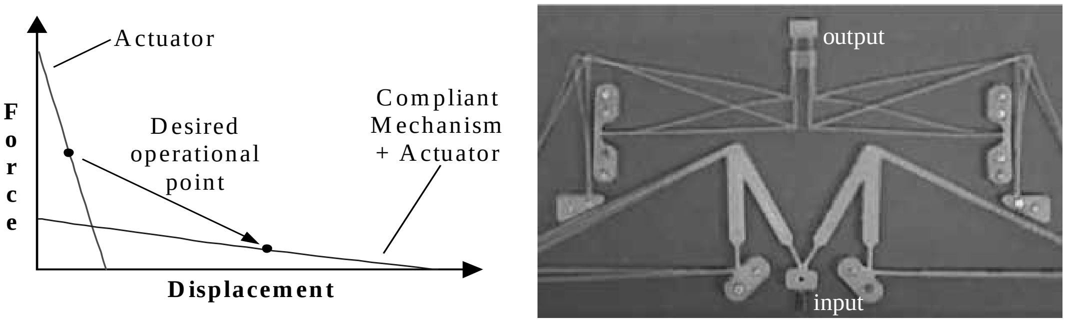


Figure 3: Adaptive Compliant Wing with an embedded compliant mechanism provided 6-degree leading edge camber change on demand. Wind Tunnel test results showed a 51% increase in lift-to-drag ratio and a 25% increase in the lift coefficient for a 6-deg. LE camber.

1.2 Active flow control systems

Mixing high energy air in the outer regions of the boundary layer with low energy air near the surface has been shown to improve flow attachment of airfoils with slope discontinuities and/or operating at heightened angles of attack. Many boundary layer flow control concepts have been studied and developed to varying degrees in prior research efforts described by Schubauer and Spangenberg[7] and Lachmann[8]. The two active flow control concepts that form the basis for the high frequency micro vortex generator research are the Pulsed Vortex Generator Jet (PVGJ) concept of McManus[9] and Oscillatory Control of Separation, Wygnanski[10]. In our concept, a vortex generator blade is mechanically oscillated at the surface to "pulse" vortex production. The blade in effect produces a coherent helical vortex structure that moves high momentum air towards the surface replacing the retarded low energy air and produce strong, coherent vortex structures that trail downstream. The advantage of this concept is that the vortex generator blade produces a stronger vortex as Mach numbers increase, whereas pneumatic techniques must drastically increase flow rates to adequately energize the boundary layer. However, achieving mechanical deployment of a vortex blade to "pulse" the vortical flow across a large frequency spectrum from a compact, lightweight, low-power actuator is not a trivial task. Scaling effects necessitate pulsing frequencies as high as 400 Hz for transonic conditions.



(a) (b)

Figure 4: (a) Actuator-Tailoring using Compliant Mechanisms - the Desired Displacement Amplification is to be Provided by a Compliant Mechanism; (b) Deformed and Un-deformed Positions of a Compliant Displacement-Amplification Mechanism. Note the Magnitude of Input and Output Displacements

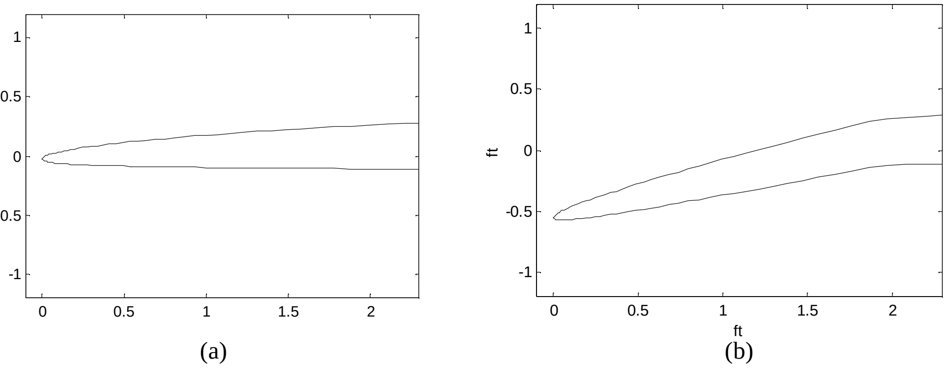
Techniques to actuate the vortex generator are limited due to the achievable power density available from actuation sources (pneumatic, electromagnetic, ferroelectric, etc.) in addition to inertia, friction, thermal, and structural limitations. Piezoelectric actuators are attractive for high-frequency applications due to the high bandwidth of longitudinally expanding stack actuators (as opposed to bimorph configurations). These actuators can also produce significantly large forces, much greater than required by flow control systems. Unfortunately, the displacement of these stack actuators fall well below that required by most micro vortex systems where required displacements range from 2 mm to 10 mm. By utilizing compliant mechanisms to amplify the displacement of piezoelectric stack actuators (trade force for displacement), it is possible to develop a compact, energy-efficient actuator that can meet the displacements and frequencies needed for active flow control applications. Figure 4 illustrates the type of motion amplification compliant mechanism used to drive the high frequency vortex generator.

2. VARIABLE GEOMETRY LEADING EDGE FLAP

The purpose of the variable geometry leading edge was to challenge compliant mechanism technology to create a camber morphing mechanism that can maintain structural integrity under severe loads required by modern fighter aircraft. The design study essentially called for a retro-fit, or replacement, of an existing high performance fighter leading edge flap. This approach was valid to compare baseline power and weight with a base-line conventional flap design.

2.1 Design approach

Design specifications for the compliant leading edge were developed in consultation with AFRL. These design requirements were then utilized to design a compliant LE to fit within the same space constraints while minimizing the weight and power requirements. Our goal was to estimate the weight and power required to operate a compliant LE while achieving the required shape morphing targets over a range of flight maneuvering conditions. The mission envelope for the compliant LE was 0.9 – 1.6 Mach and 0 – 15 degrees angle of attack. Aerodynamic optimization was performed to maximize the lift-to-drag ratio over a range of speeds, angles of attack, and flap deflections, while eliminating flow separation. High speed maneuvering of the baseline flap limits the maximum deflection to 15 degrees (greater deflections are available for low speed maneuvers); consequently, the compliant leading edge flap was limited to a 15 degree range of motion. As noted by the optimized shapes shown in Figure 5, the leading edge optimized profile was close to a “rigid hinge” flap with a softened radius at the pivot point. Consequently the target shapes do not fully exploit the benefits of camber changing compliant structures; however, our goal was to match these shapes as closely as possible as they maximized the maneuvering capability of the fighter.



(a) (b)

Figure 5: Leading edge shape morphing problem specifications from aerodynamic optimization (XonTech Inc.), (a) 0 degree (nominal) flap deflection, (b) 15 degree flap deflection

With the undeformed and deformed shapes specified along with the external air loads, a structural optimization problem was formulated to determine the flap design. It is desired to make the compliant mechanism flexible enough to undergo intended deformation by expending minimum actuator energy; however, it should be also be stiff enough to withstand the external air loads within structural and aeroelastic constraints. The optimized compliant structure embraces these conflicting design requirements. Effectively, the compliant mechanism is 400 times stiffer relative to external aerodynamic pressure loads (actuators locked) than it is for the actuators to cause intended deformation alone (no pressure load). The optimization algorithm effectively develops a structure *that has maximum stiffness relative to external loads and minimum stiffness relative to intended deformation*. This ensures that the actuator is primarily working against the reaction forces created by the aerodynamic loads while providing minimal effort deforming the structure.

2.2 Estimation of power and weight

Based on sizing information from three-dimensional finite element models, weight and power estimates were made for the compliant flap, relative to the baseline hinged flap. Power requirements were calculated by treating the worst-case pressure load as a constant follower force. Table 1 summarizes the net torques and power changes.

Table 1: Power increase of compliant structure flap over modern conventional figher-jet flap

Flap Deflection	ΣT_{pres}	$\Sigma(T_{pres}+T_{struct})$	**ΔPower**
0^o	114,700 in-lb	109,740 in-lb	4.3% decrease
15^o	114,700 in-lb	119,780 in-lb	4.4% increase

The weight of the compliant structure was estimated by multiplying the volume of each member by the appropriate material density. Additionally, the weight of each rotary actuator was calculated using formulas governing weight, stiffness, diameter, etc. obtained from Curtis Wright Motion Systems. Table 2 summarizes the results of these studies. The full composite design utilizes composite materials wherever possible, the partially composite compliant structure utilizes composites primarily in the wing skin while the compliant mechanisms and actuator transmission system are titanium and steel respectively. As is evident from Table 2, much of the weight increase is due to retro-fitting the current flap actuation system. The compliant structure in fact offers weight reduction over the current flap structure. Rather than adopting the current rotary actuation scheme, an alternate actuation scheme might further reduce the weight of the compliant leading edge flap.

Table 2: Weight comparison of compliant structure flap over modern conventional fighter-jet flap

Weight Comparison Study	**With current Actuation System**	**Compliant LE Flap Structure**	**Total Weight**
Full Composite	55% increase	22% decrease	7% increase
Partial Composite	86% increase	4% increase	35% increase

3. VARIABLE GEOMETRY TRAILING EDGE FLAP

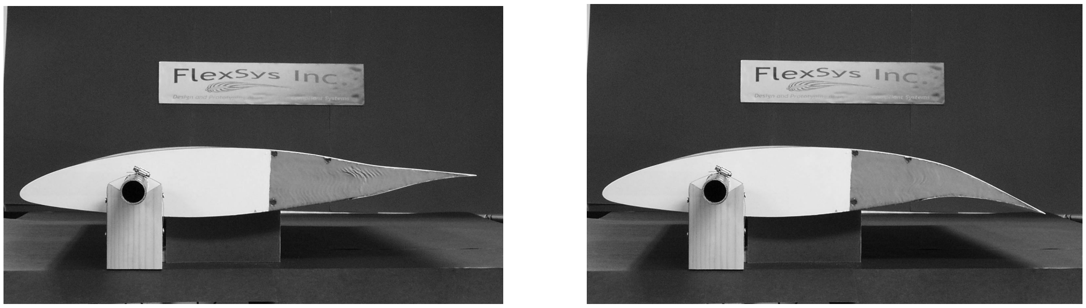
Endurance aircraft experience weight variations as much as 50% or more during a typical mission. Therefore, minimizing wing drag over a wide lift range is critical for mission efficiency. The purpose of the variable geometry trailing edge flap was to create a seamless, hingeless flap that could effectively change wing camber and minimize drag over a wide lift range. In comparison, deflecting a conventional flap to try and accomplish this produces flow separation and increased drag. A wind tunnel prototype is presented that was used to validate the low drag properties of the airfoil.

3.1 Design approach

Design specifications for the trailing edge flap were determined by consulting AFRL. The primary goal was to develop a variable geometry trailing edge flap for a concept high altitude, long endurance air vehicle configuration. Based on the required mission profile, FlexSys Inc. set out to design a flap that would be capable of a +10 to –10 degree flap deflection. In addition, the design required that the flap could deflect differentially along the span in order to vary the deflection and optimize wing loading. Target shapes were determined from an algorithm that produced the smoothest possible shape change given the desired flap deflection. Three-dimensional finite element models were developed to study three dimensional effects including actuator placement, flap stiffness, fatigue strength, and dynamic characteristics. On going work is currently looking at full-scale aeroelastic simulation of the flap in order to predict flutter response. Results of this simulation will be used to finalize the weight and power requirements of the full-scale flap design.

3.2 Wind tunnel model

In parallel with the trailing edge design study, a prototype wind tunnel model was constructed to validate aerodynamic performance of the intended shape change. Figure 6 shows photographs of the wind tunnel model with the variable geometry compliant trailing edge flap. The FlexSys trailing edge flap provides the variable geometry necessary to minimize drag throughout a long endurance reconnaissance mission. The flap deflects +10 to -10 degrees at speeds up to 20 deg/sec using conventional (internal) electromechanical actuators. Additionally, the flap can twist differentially up to 1 degree per foot over the span of the prototype. This model was tested at the Ohio State University wind tunnel facility in the Fall of 2002.



(a) (b)

Figure 6: Variable geometry TE wind tunnel model shown in -10 degrees (fig a) and +10degrees (fig. b) positions

3.3 Aerodynamic benefits

Because endurance aircraft experience weight variations as much as 50% or more during a typical mission, minimizing wing drag over a wide lift range is critical for mission efficiency. The compliant variable geometry trailing edge flap provides a distinct performance advantage over a conventional trailing edge flap. This point is easily illustrated using experimental wind tunnel data. Figure 7 presents wind tunnel aerodynamic data[11] for a typical modern high altitude long endurance airfoil with a conventional 20% chord trailing edge flap. The data shows conclusively that deflecting a conventional flap downward increases the airfoil lift coefficient; however, for the two positive flap deflections shown, airfoil drag is simultaneously increased. This drag rise is caused by flow separation in the pressure recovery region on the aft portion of the airfoil upper surface. This region of flow separation is induced by the sharp increase in radius of curvature on the airfoil upper surface as the conventional flap rotates downward. Notice that airfoil drag performance is still acceptable when the trailing edge is deflected up. In this position there is a decrease in radius of curvature on the upper surface, and while deflecting the flap trailing edge up limits airfoil lift, the flow is still fully attached on both airfoil surfaces.

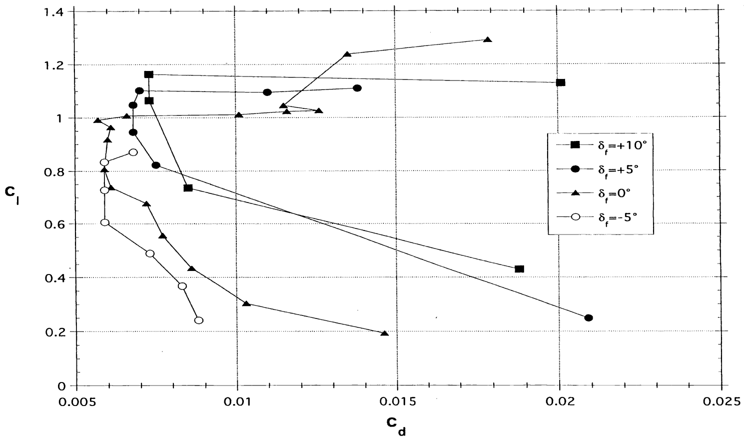


Figure 7: Cl Vs. Cd data for a modern long endurance airfoil with a conventional trailing edge flap[11]

Data taken at the Ohio State University low speed wind tunnel is shown in Figure 8. Here, the adaptive compliant flap shows much better drag control than is possible with a conventional flap design. When a variable geometry compliant trailing edge flap is used, the process is such that the radius of curvature on the airfoil upper surface can be contoured for maximum flow attachment in the pressure recovery region. Notice that consistently low drag levels are maintained as the flap is deflected downward and the airfoil aft upper surface is continually reshaped during the deflection process. Compare these results with those presented in Figure 7, and the aerodynamic advantage of using a variable geometry trailing edge for endurance aircraft applications becomes quite obvious.

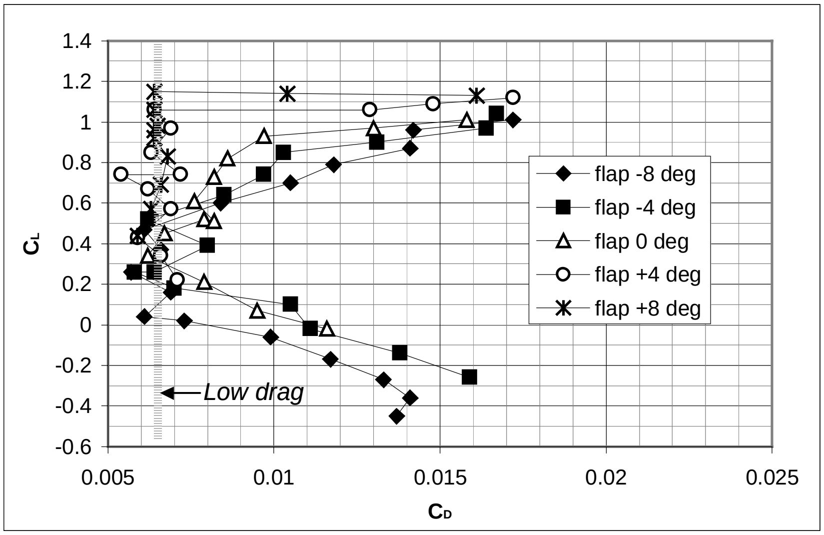
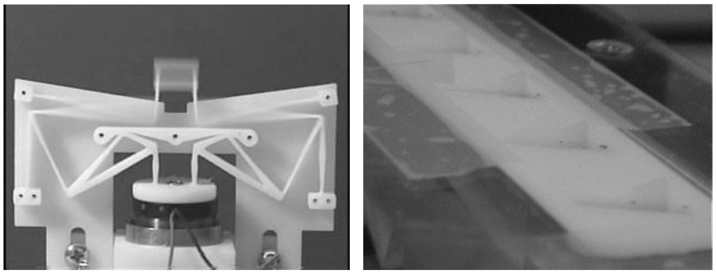


Figure 8: Wind Tunnel results highlight the benefits of FlexSys variable geometry trailing edge flap. As the flap angle is changed from -8 degrees to +8 degrees, the CL increases from 0.1 to 1.1 without increasing the drag. Note the low drag envelop (C_D = 0.0065) during the entire excursion.

4. HIGH-FREQUENCY VORTEX GENERATORS

This project was undertaken to design and demonstrate a mechanical active flow control device that could achieve flow separation control characteristics competitive with pneumatic systems developed and demonstrated by McManus[8] and Wygnanski[9]. It was desirable to create a mechanical (blade) vortex generating system effective at both subsonic and transonic flow conditions, since many of the current pneumatic systems are inefficient when used to control flow separation in a transonic flow environment. Figure 9 shows a High Frequency Micro Vortex Generator (HiMVG) device developed and demonstrated by FlexSys Inc. and the University of Michigan, during a Phase I STTR program[12, 13]. The seven-blade array depicted is capable of operating at deployment frequencies as high as 90Hz. The design is based on a patented compliant motion amplifier[14].



(a) (b)

Figure 9: (a) The High-frequency Mechanical Vortex Generator (HiMVG) running at 150Hz with 5mm displacement due to a compliant motion amplifier integrated with a voice-coil motor- (b) Close-up of the Vortex Blades Moving at 90 Hz Through the Slotted Cover Plate on the Surface of the Prototype Wing inside a wind tunnel.

4.1 Design approach

A majority of the effort was expended on the design of a compliant amplifier. The goal was to design a motion amplifier that amplifies the displacement input from an actuator (0.25 mm) to produce 5 mm at the output (20 times displacement amplification). The actuator integrated with the motion amplifier was designed to operate in the frequency range from 0 to 300 Hz. The phase I system was designed around a high-speed voice-coil motor. Various loading, displacement and material properties were input into the optimization. Shown in Figure 9 (a), the voice coil amplifier system produced satisfactory results, obtaining deployment frequencies of the vortex blades as high as 90 Hz (high enough for experimental requirements). However, the original goal was to design a vortex generator with deployment speeds as high as 300 Hz. In addition, the voice coil motor required a substantial amount of power (on the order of 80 Watts) to power the system at the 90 Hz deployment frequency. These shortcomings of the phase I amplifier-actuator have been significantly improved during a follow on Phase II program. Using newly developed optimization tools, FlexSys Inc. was able to design a successful motion amplifier with 50:1 displacement amplification. Shown in Figure 10, the motion amplifier mates with a low voltage piezoelectric stack actuator (Piezo Systems Inc.) to produce up to 2 mm of output displacement and a block force up to 7 N across a frequency band from 0 to 400 Hz. Measuring just 64 mm x 32 mm x 10 mm, the piezo-compliant amplifier system uses approximately 25 Watts peak power to achieve deployment at these high speeds (average power is significantly less). This new actuator system will be tested as a flow control concept for dynamic (pitching) airfoil systems. Testing is schedule for later this year.

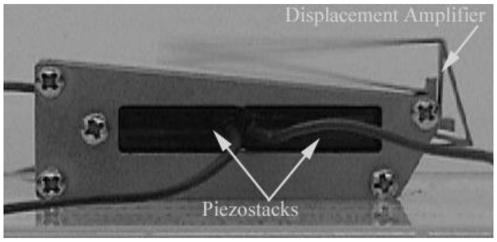
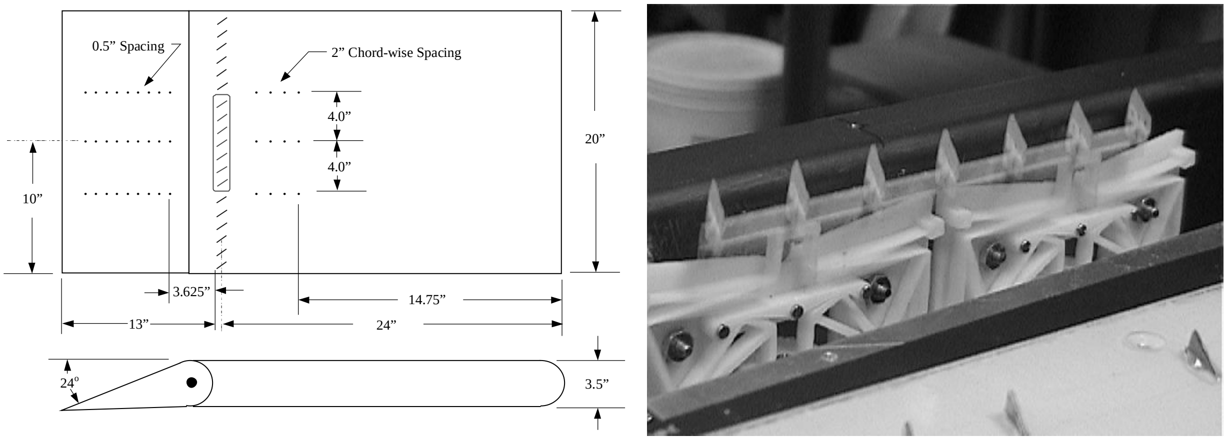


Figure 10: Piezostack actuator integrated with a 50X compliant motion amplifier (steel) running at 400 Hz with over 2mm displacement.

4.2 Wind tunnel test article

A phase I wind tunnel model was developed for testing the flow separation performance of both the static and dynamic vortex generator arrays. This test article, shown in Figure 11, consists of a flat plate forward portion with a rounded leading edge and a trailing edge flap with adjustable angle settings.



(a) (b)

Figure 11: HiMVG Experiment: (a) Wind tunnel model design details (b) Dynamic HiMVG test model without cover plate

Testing was accomplished at the University of Michigan low speed wind tunnel facility at speeds of 50 ft/sec. and 70 ft/sec. Figure 12 illustrates data from the wind tunnel tests. This data plots model upper surface negative pressure (suction) in inches of water for the upper surface, centerline, static pressure taps, over a range of vortex frequencies. With no vortex generator blades and with static vortex generator blades, the flow separates at the base of the flap as indicated by the lower (negative) pressure plots. Operating the deployable vortex generators in a high frequency mode produced flow attachment on the flap upper surface, tap positions 5 through 13, where none was present with the vortex generator blades statically deployed. For a test velocity of 70 ft/sec., the optimum flow attachment was obtained at a frequency of 70 Hz, which closely follows the pneumatic subsonic flap flow control results of Wygnanski.

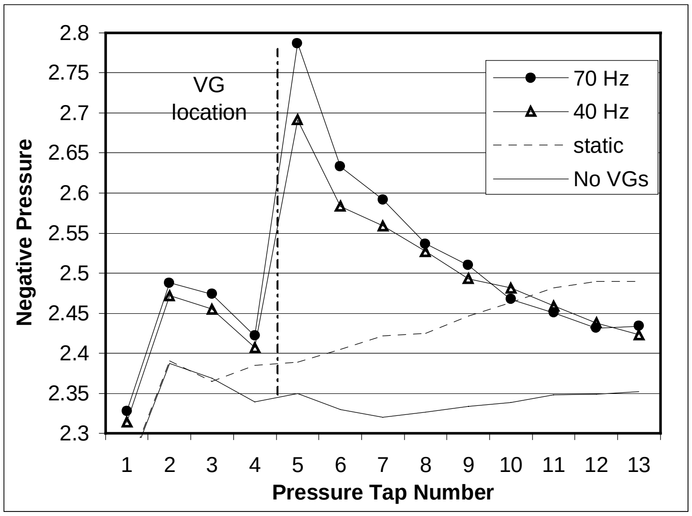


Figure 12: Negative pressure distribution over the surface of the wind tunnel test article. Optimum flow attachment was achieved at a pulsing frequency of 70 Hz.

5. CONCLUSIONS

Compliant mechanisms represents a novel and scalable approach for the design of morphing aircraft structures. This paper highlights ongoing research at FlexSys Inc., in collaboration with AFRL Air Vehicles Directorate to develop innovative shape morphing systems. The development of compliant mechanism technologies for shape morphing aircraft structures suggests that marked improvement in air vehicle performance can be realized. Variable geometry compliant leading and trailing edge flaps can provide mission adaptive wing capability without significant weight, space, or power penalty. Wind tunnel results for a long endurance airfoil compliant trailing edge flap demonstrated the ability to produce low drag over a wide range of lift. The benchmark study on the fighter leading edge flap demonstrated that it is possible to design variable geometry wings that are subjected to large air loads without compromising overall weight, space, or power requirements. High frequency vortex generators were developed and demonstrated by integrating voice-coil motors and piezoelectric stack actuators with compliant motion amplifiers to produce active flow control systems that can extend flow control performance into the transonic regime. Continued research and development will make these and many other shape morphing applications a reality.

6. ACKNOWLEDGEMENTS

The work on shape morphing wing surfaces is funded by an SBIR Phase II contract to FlexSys Inc. through Air Force Research Labs. Program monitoring is performed by AFRL Air Vehicles Directorate with additional consultation provided by Lockheed Martin Aeronautics Company. The authors gratefully acknowledge the technical support and oversight provided by Mr. Michael Love and his colleagues at LM Aero. The work on Active Flow Control using High Frequency Vortex Generators was funded by an STTR Phase II contract to FlexSys Inc. and University of Michigan through Air Force Office of Scientific Research. The authors gratefully acknowledge the technical assistance provided by Mr. Donald Geister (University of Michigan) in preparation and execution of wind tunnel experiments.

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