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HIGH AUTHORITY MORPHING STRUCTURES

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ABSTRACT

Recent advances in actuation technology and multifunctional materials have presented a unique opportunity to develop structures that have the ability to morph to a variety of shapes while under significant load constraints. One of the many applications of these “high-authority” systems is for morphing air wings for control and drag reduction. The exciting solution to this is the creation of a statically determinate structure that incorporates linear actuators to produce morphing capabilities. Statically determinate structures satisfy Maxwell’s necessary condition that the number of member forces equal the number of joint equilibrium equations. By imposing this condition on the structure it is possible to actively change the shape of the overall structure without resulting in failure. In a morphing foil, the only induced strain within passive members will be due to the hydrodynamic forces present. Deformation of the truss members is *stretch-dominated*—they do not experience bending—and thus improve the load carrying capacity of the structure. Of primary interest are Shape Memory Alloy (SMAs) actuators. SMAs are useful for shape morphing concepts where large forces are needed. A prototypical foil has been built around a statically determinate structure that incorporates linear actuators to produce morphing capabilities. These “smart” foils have been tested in a wind tunnel to examine their drag reduction capabilities.

Keywords: Lattice truss structure; Statically determinate; Shape memory alloy; Morphing wing

1.0 Introduction

Aerodynamic shape optimization in the design of aircraft has shown that a significant reduction in fuel consumption is possible if wings are able to change shape to reduce the drag coefficient for a given flight condition [1]. The potential reduction in drag has been calculated to be as much as 6% for conventional wing design and this will increase if new materials and structures are utilized. An aircraft wing that functions as a “smart structure”—one that continually monitors its environment and adapts to minimize drag—would revolutionize aircraft design. Additionally, a single shape-changing structural element has the potential to replace separate load bearing and actuating systems (e.g. hydraulic flaps). Proof-of-concept structures are being designed to demonstrate this principle.

Metallic sandwich panels with periodic, open-cell cores are being considered for use in demonstrating a stiff, yet lightweight morphing wing structure. Manufacture of these structures has been made possible by advances in fabrication techniques and design tools. Recent studies have demonstrated that if these structures are designed to be statically determinate, they can be used for large load bearing applications with added morphing capabilities [2-4]. These ideas have been adapted for a morphing aerofoil. A foil has been designed to integrate linear actuators within the structure. It has been tested in a standard wind tunnel to examine the effect on drag and lift due to actively changing its shape using the actuators. Preliminary testing has shown changes in lift and drag are possible due to small changes in shape to the foil profile. Further testing is required but these results demonstrate that morphing lattice structures have the potential to be used in the next generation of aerospace vehicles.

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2.0 Statically Determinate Structures

The creation of a statically determinate structure, which incorporates linear actuators, gives us the opportunity to design a foil with morphing capabilities. Statically determinate structures satisfy Maxwell's necessary condition that the number of member forces equal the number of joint equilibrium equations [5, 6]. For a pit-jointed frame of *b* struts and *j* frictionless joints, the criteria for 2 and 3 dimensions are: $b = 2j - 3$ and $b = 3j - 6$ respectively. Imposing this condition on the structure presents a unique opportunity to actively change the shape of the overall structure without resulting in failure. For example, when a strain (e.g. a thermal strain) is induced in an individual member of the structure, no elastic strain energy is stored within the remaining members. Therefore, by replacing a passive member with a linear actuator that can contract or expand, this actuator can create a shape change in the entire structure. A two-dimensional lattice structure is the foundation of the morphing foil with passive members being replaced by linear actuators. Theoretically, the only induced strain within the truss members (active and passive) will be due to the hydrodynamic forces present. The load carrying capabilities of these structures are further enhanced by the fact that deformation of the truss members is *stretch dominated*—they do not experience bending. Bending is detrimental to the mechanical properties of different material systems (e.g. stochastic foams). The elimination of bending is key to maintaining the integrity of the truss structure as external loads are applied [7]. Lu, Hutchinson and Evans (2001) and Lu and Evans (2002) have described flexural actuators that are able to realize large bending displacements while under large restraining moments (Figure 1). For example, compared to a simple bimorph actuator, the corrugated core structure can carry a significantly larger force over the same distances for the same actuator weight (Figure 2) [2]. The first working demonstration of "high authority" (large load-bearing capacity with large displacements) structures proved the feasibility of such morphing systems (Figure 3). This model was designed using theoretical results given by Lu *el al.* [2]. The 2D specimen was manufactured using rapid prototyping techniques from Acrylonitrile Butadiene Styrene (ABS). Shape memory alloy wire was trained to contract by 4% when heated to the activation temperature. It was bonded to the ABS structure to become the top face sheet. In this demonstration, actuation of the active elements (SMA wire) produced significant end tip displacements even in the presence of a large restraining moment. It was shown that the weight-to-load capacity of this morphing structure exceeded 100.

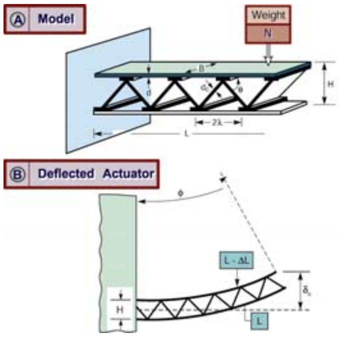

Figure 1: Statically determinate corrugated core. [After Lu *et al.* (2001)]

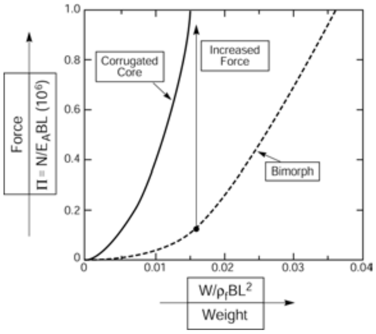

Figure 2: Minimum weight plotted as functions of load index Π for NiTi/Si corrugated beam and bimorph. [After Lu *et al.* (2001)]

Figure 3: Demonstration of load bearing capacity of statically determinate corrugated core structure.

3.0 Materials and Methods

3.1 Lattice Truss Structures

A standard air wing profile was chosen for the design of the model. Using an aerofoil design program (DesignFoil) the foil *NACA 6415* was chosen as the template for the morphing foil. This describes the trace of the outer edge of the airfoil model. A two-dimensional truss structure was incorporated within this template to which linear actuators can be attached (Figure 4). Airfoil samples were manufactured using rapid prototyping technology (Stratasys FDM 3000) from Acrylonitrile Butadiene Styrene (ABS). The internal structure was designed to be able to accommodate several linear actuators. The first wind tunnel ready prototype was designed to hold six linear actuators. Two sets of three actuators are placed in parallel to induce shape changes in the foil. It is possible to independently control each individual actuator. For the purpose of this preliminary study, all actuators were activated simultaneously to produce “flapping-like” deformation. However it is possible to produce twisting deformation of the foil through independent control of individual actuators.

3.2 Linear Actuators

For these preliminary tests, shape memory alloy (SMA) linear actuators were chosen to produce the shape changes in the airfoil. Shape memory alloys are of great interest for shape morphing concepts where large forces are needed. The very high forces that can be exerted are a result of the high yield strength (~600MPa) of these materials. The contractual actuation strains are as high as 8%. Nickel Titanium (Trade name Nitinol) SMA is trained to recover its austenitic structure when heated to its upper transformation (Austenite finish, A_f) temperature [8]. The training process involves annealing the material at 525C for ~30 minutes. Martensitic phase transformation absorbs the inelastic tensile strains (up to 8%) applied to the material. Recent advances in manufacturing technologies have resulted in high speed and high efficiency actuators able to produce precise actuating strains. *Nanomuscle, Inc* (Antioch, CA) linear actuators were used within the truss core of the foil to produce changes in shape. Each actuator (NM195) can exert a contractual force of 195 grams. Each actuator requires 4.5V at 915mA to allow contraction at rates of 120 cycles per minute. Higher actuating frequencies can be achieved if the voltage is increased. Examples of these SMA linear actuators fitted to a simple two-dimensional truss structure are shown in Figure 4.

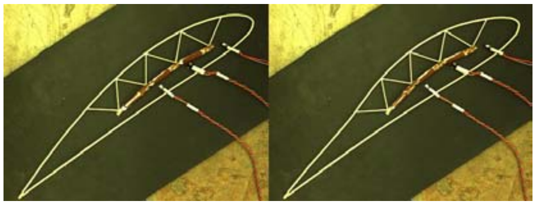

Figure 4: An initial design with no actuation (left) and with all actuators contracted (right). Notice deformation induced on top surface.

3.3 Experimental Procedure

Based upon the preliminary design shown in Figure 4, an airfoil model suitable for wind tunnel testing was designed and built using the Stratasys FDM 3000 system. A computer-aided drawing of this first generation foil is shown in Figure 5. The foil has a span width of 150mm, chord length of 300mm, and a maximum thickness of 45mm. The wind tunnel wing section model was designed to withstand high airspeeds yet still accommodate shape changes due to actuation. This design also features a reinforced trailing edge to increase the stiffness of the design. Additionally, the sides of the foil were sealed using a compliant polymer film to eliminate drag effects from flow entering the sides.

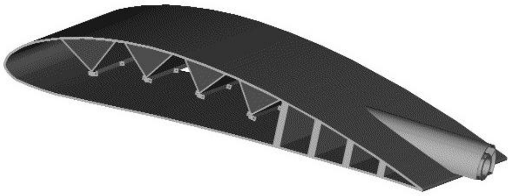

Figure 5: Prototype airfoil model (six inches wide), featuring three rows of actuator attachments.

The specimen was tested in a wind tunnel with a 12” × 12” cross section. The experimental model is shown in Figure 6.

The tunnel can produce airspeeds up to 145mph in the test section. The foil was mounted onto a sting that measures the normal and axial forces, and the angle of attack. The aerodynamic forces of lift and drag can be found from the following relations:

$$Lift = N\cos\alpha + A\sin\alpha$$
$$Drag = N\sin\alpha + A\cos\alpha$$

where N = normal force, A = axial force, and α = angle of attack. The lift and drag force produced by a particular foil can be found from:

$$L = \frac{C_L \rho U^2 S}{2}$$
$$D = \frac{C_D \rho U^2 S}{2}$$

where C_L = coefficient of lift, C_D = coefficient of drag, ρ =density of air, U = airspeed, and S = plan area of the airfoil. Using this relation the coefficient of lift and drag can be determined. Due to the sensitivity of the sensors it is ideal to test the foils at as high airspeed as possible to take accurate measurements of lift and drag. Several tests were performed to determine the change in normal and axial force acting on the sting. For each test the airspeed was steadily increased till a measurable a change in these forces was recorded.

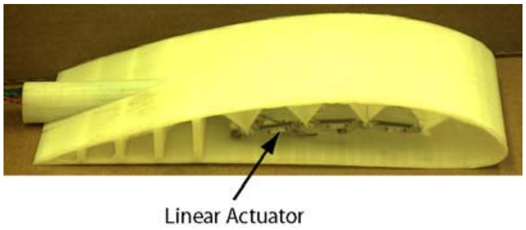

Figure 6: Airfoil prototype with SMA linear actuators attached

4.0 Preliminary results

The tests performed in the wind tunnel used an angle of attack $\alpha = 0$. Therefore the axial force and normal force correspond directly to the drag and lift of the foil respectively. Upon activation of the SMA linear actuators (NM195; *Nanomuscle, Inc*), the profile of the airfoil increased in height by approximately 10%. As the airspeed was incrementally increased these was a measurable change in lift and drag. These changes are recorded in Table 1. The highest velocity during the test was set at 85mph. At higher velocities the airfoil started to vibrate significantly and the test had to be discontinued.

Over time, as measurements were being made for increased airspeed, the change in profile diminished. This was due to the SMA actuators experiencing excessive heat loads, which results in a loss of the shape memory effect. Also micro cracks were found in the ABS structure after repeated actuation.

Airspeed	Normal Force (lbf)			Axial Force (lbf)		
(mph)	Unactuated	Actuated	Difference %	Unactuated	Actuated	Difference %
50	0.70	0.72	2.86	0.17	0.19	11.76
55	0.77	0.80	3.90	0.20	0.20	0.00
60	0.88	0.91	3.70	0.22	0.23	4.55
65	1.06	1.10	3.77	0.27	0.28	3.70
70	1.24	1.27	2.42	0.33	0.34	3.03
75	1.41	1.48	4.96	0.39	0.40	2.56
80	1.53	1.60	4.58	0.41	0.46	12.20
85	1.81	1.72	-4.97	0.50	0.46	-8.0

Table 1: Model fully functional – there was a noticeable change in shape at every actuation. Data collection stopped at 85 mph due to vibration instability.

5.0 Discussion

The preliminary results clearly demonstrate the ability to integrate static structures with linear actuators to produce changes in shape. It has also been shown that this technology has the potential to be applied to morphing airfoils for drag reduction and control of surfaces. The results show a small percentage change in both normal and axial forces acting on the airfoil, when the internal linear actuators are actived. However there is some fluctuation in these results at low airspeeds. Additionally, the use of ABS as the material for the static structure is problematic. As the airspeed is increased the structure began to vibrate excessively and the experiment was shut down. Although the assumption is made that the system is statically determinate, the truss members of the structure are not free to rotate at the nodes—they are not pin joints. Due to the rapid prototyping manufacturing process and that bending stresses are generated at the nodes, small micro cracks developing throughout the structure. Continual actuation causes these cracks to grow and reduce the potential shape change of the system.

6.0 Future Work

More complete testing must be carried out to demonstrate the ability of these morphing structures for drag reduction. The airfoil will require a more rigid design in order for measurements to be taken at high airspeeds. Designs are currently being developed to manufacture a foil from aluminum alloys. Focus is also directed towards three-dimensional statically determinate core structures for morphing airfoil design. These structures will be designed to not only change the profile to influence drag and lift but also for flight control. For example these foils will be able to produce twisting due to predetermined actuation of specific actuators.

Ultimately, the system will integrate sensor technology to continually monitor flight conditions. This information will be used to control actuation to produce optimal profile shapes.

7.0 Acknowledgements

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8.0 References

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