A REVIEW OF OPTIMISATION OF MORPHING SURFACES FOR INCREASED AERODYNAMIC PERFORMANCE

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ABSTRACT

Morphing surfaces, when correctly implemented, have immense potential to increase the efficiency of systems that are in direct contact with the fluidic flow. Taking inspiration from birds, the idea of morphing expresses how instead of having different moving parts, a single albeit complex, shape-shifting, and twisting surface can prove to be more efficient. This paper can be largely divided into two parts. The former gives a brief overview of the classifications in the field and methodologies of morphing surfaces, while the latter part deals more with aspects of their implementation and designing an optimal control structure. The problems and solutions associated with their implementation are presented along with prospects. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

KEYWORDS: Morphing, Variable Shape Structures, UAVS, Shape Memory Alloy

NOMENCLATURE

- AR = Aspect Ratio
- b = wingspan
- c = wing chord
- C_L = Lift coefficient
- C_D = Drag coefficient
- C_P = Pressure coefficients
- M = Mach number
- Re = Reynolds number
- t = Time
- U_∞ = Free stream velocity
- α = Angle of attack, deg
- β = Angle of sideslip, deg
- λ = Wing taper ratio

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INTRODUCTION

Morphing techniques or similar actively deployable surfaces are highly dependent on an integrated sensor network. However, such a nexus of sensors has its limitations such as

- Cable management complexities
- System integrity in cases where a series configuration is required over its parallel counterpart

- Maximum cap on the strain allowance, especially in cases where a super-deformable material is to be used.
- Unreliable silicones and foam bonding

Certain workaround methods for the above solution exist, such as employing a wireless system thereby making the integration and installation of sensors far more manageable, removing the need for architecture unpacking. Such a methodology would take advantage of the simplicity with which sensor nodes can be placed and made to adapt. *Wireless sensor network* (WSN) refers to a group of spatially dispersed and dedicated *sensors* for monitoring and recording the physical conditions of the environment and organizing the collected data at a central location [1, 2]. Such a system would also bring about additional problems, for instance, mutual interference and high transmission power.

For high curvature surfaces, spraying of sensors can make them independent of geometric shapes. Spraying methods have evolved drastically from uncontrollable to present-day pressurized systems. In cold spraying process, a surface is bombarded with a stream of micro-particles (about 50 μ m) at very high velocities (300-1500 m/s) which are driven through a gas in a pressurized chamber, below the melting point of the material. Cold sprays, by employing low temperatures, minimize the effects of residual stress and excess gas release and their low oxygen levels contribute to them exhibiting bulk-like properties for electrical and thermal conductivity.

By ceaseless monitoring at substructural levels, reliable data about the integrity of each system can be procured down to 5mm. This can be accomplished by using fiber optic cables and their backscattered light. For larger components, [3] utilized the time of the backscattered light to know the location of the reflection. Other improved methods can also be seen in [4 - 6]

For ease of understanding, consider every rib in the trailing edge of a morphing wing is connected by actuation mechanisms, which in turn are connected to a longitudinal stiffening element. As proposed in [7], such a mechanism, known as oscillatory glyph mechanism would prove to be efficient and robust at the same time by making the actuation rod oscillate between two extreme positions at different speeds, and hence have a widespread use where a quick return mechanism was required. In paper [8], the same design was modified which mainly relied on the reversal of the mechanism itself. Other such applications include the SARISTU (Smart Intelligent Aircraft Structures) and CRIAQ (Consortium for Research and Innovation in Aerospace) projects undertaken by Airbus and Bombardier respectively. The SARISTU project revolved around the creation of an adaptive trailing edge device (ATED) using Fiber Bragg gratings using closed-loop control to achieve a given set of target cambers. The shape information is converted into strain information using an optical fiber transducer. The shape sensor consists of a beam running laterally with slots for housing the optical fiber cable on the upper and lower parts. Consisting of four support joints, the first and major support is affixed while the rest form the required camber of the ATED. All supports are directly joint to the inner skin surfaces. The sensor assembly is designed to follow the morphing of the ATED. To obtain the shape of the sensing strip at a particular stress level, the Frenet – Serret formulas are used.

Differential geometry principles demonstrate that a “shape” can be defined as a group of scalar and vector quantities along a curvilinear abscissa (s): the curvature $\kappa(s)$, torsion $\tau(s)$, tangent vector $T(s)$, normal vector $N(s)$, binormal vector $B(s)$, and position vector $r(s)$. This means that given the relation between the strain at a certain location $\epsilon(s)$, and the half-thickness of the Sensor Beam $y_{\max}$:

$$k(s) = \frac{\varepsilon(s)}{y_{\max}} \quad (1)$$

And the Frenet – Serret formulas can be applied as-

$$\frac{d}{dx} \vec{T} = k(s) \vec{N}(s) \quad \frac{d}{ds} \vec{N}(s) = -k(s) \vec{T}(s) + \tau(s) \vec{B}(s) \quad \frac{d}{dx} \vec{B}(s) = \tau(s) \vec{N}(s) \quad (2)$$

With the initial values of $T(0)$, $N(0)$, and $B(0)$, the shape can be reconstructed by iteration where the position vector $r(s)$ of the sensor beam is computed by:

$$\vec{r}(s) = \int_0^s \vec{T}(s) \cdot ds + \vec{r}(0) \quad (3)$$

The SARISTU project proved to be a success with error < 4.3%, which was within the design limitations

DEVELOPING A CONTROL SYSTEM FOR MORPHING SURFACES

Each morphing model proposed, required movement two stable states and transitions between them. For aerodynamic morphing, the major aim is to reach the desired camber value in flight, keeping in mind flight parameters like the resistance to the movement and the structure's in flight integrity without compromising efficiency. Dimin et al. [9] presented a solution by integrating a set of actuators into the trailing edge of the wing, with the main aim being to create a secondary method for transforming the camber between $+5^\circ$ and -5° . Both feed forward and feedback control logic architectures were detailed and numerically investigated. And since morphing surfaces have the capability to surpass traditional aircraft control surfaces, the flight dynamics of the same have been studied. Li et al. [10] developed a controller encompassing the ability to morph both, the leading and the trailing edge by using two actuators and hence overcoming longitudinal instability. Fig (4) shows a simple block diagram devised for a controlling mechanism for a closed-loop system. Tong et al. [11] created a system for variable span morphing aircraft by asymmetric changes in the wing sweep angle. By using Kane's method, a multibody dynamic model was built and constrained back stepping methods were used for trajectory tracking. The stability of the presented control law was discussed in the sense of Lyapunov. Liu et al. [12] developed a system specifically for a certain type of morphing surfaces where distributed arrays of multiple shape-changing devices were used. In the domain of folding wings, Colorado et al. [13] described a system including an attitude controller named back-stepping encompassing angular acceleration functions. Simulations showed a 23% increase in net force production. For designing a control system for the actuation and sensor architecture, we look at data obtained from SMA models [14] by giving inputs such as initial alloy temperature, the applied force, and the heat generated due to the current and outputs such as actuator temperature and its displacement. For using the SMA's shape-changing characteristics, an initialization was required by an external force to pass it through the transformation phase and then subsequently into the cooling phase. In [15, 16], the controller had jurisdiction on the operation of the airfoil camber, and hence open loop. For each airfoil, there would be two values which would give the magnitude of the difference between the optimum and present vertical elongations at the 2 actuating points (assume W_1 & W_2) where the optimum displacement would be Y_1 & Y_2 . Koreanschi et al. [17] used this method of two actuating points along with an adaptive upper surface to minimize the shift between the values of C_L and C_D while transitioning from laminar flow to turbulent flow. To accomplish this, a linear variable differential transformer [LVDT] potentiometers were used. The open-loop control was designed, to equal the actual elongations i.e, X_1 & X_2 to the optimum displacement by enabling the SMA to control the elongation till the optimal point

is reached. [15, 18–25]. The schematic is depicted in fig (5). Closed Loop control systems are used for real-time airfoil generation, using information such as pressure to improve the steady-state fluid flow over the upper surface of the airfoil (fig (6)). The optimum airfoils calculated previously are used as reference points and the closed-loop system is allowed to calculate its steady points, which are then compared to the known values.

Figure 1: Simple Block Diagram Devised for a Controlling Mechanism for a Closed-Loop System.

Figure 2: Open-Loop Control System.

Here two branches i.e, gradient ascent and simulated annealing are merged [29] because the cost function depends on the decrement of the C_D and maximization of C_L/C_D , and hence a gradient ascent method alone was not suitable. Not only was it more accurate, but this structure also proved to be faster in terms of determining the value of the transition points.

Optimization Control

Designing a morphing surface is always a balancing act between the weight, power consumption, cost, and the effectiveness of the system itself. Thus the objective functions can be classified topology optimization [30-32], parameter or gradient-based optimization, and evolutionary optimization algorithms.

Topology optimization is generally utilized for morphing the leading and trailing edges. Tong et al. [31] devised a system for leading-edge morphing by using glass fiber reinforced epoxy composites, built by using solid isotropic material with penalization (SIMP) method and an objective function was used to minimize the LSE between the deformed and desired camber values. Multi-objective population-based increment methods were used to find the optimal percentage of change in the C_L , buckling factor, and the total mass of the structure. Gradient-based optimization is often used along with another method that is concerned with computing the required roots of the derivatives for a given aerodynamic situation. Nitin et al. [33] proposed a shape optimization tool for 3D lifting surfaces for operations in viscous and incompressible environments. A flapping wing configuration as described previously was considered in [34] for maximizing the propulsive efficiency. Zhoujie et al. [35] quantified the results of the aerodynamic analysis and highlighted the benefits of using a trailing edge configuration along with aerodynamic design optimization. However, the most widespread method for morphing is evolutionary-based. By using parameters for describing, the external planform of the wing section, the actuator along their positions, and internal compliant structure, Molinari et al [37] showed an approach to optimization.

Figure 3: Closed-loop Control System.

The wing was actuated using SMA embedded into the structure and the internal compliant structure used primarily for guiding the morphing is described by a Voronoi graph-based parameterization. Thus by using a combined approach, the resulting airfoil section can produce a morphed cambered airfoil, when actuated and also when inactive, hence providing the required aerodynamic efficiency. Kai et al. proposed a method for approximating a shape change of morphing surfaces, by using revolute joints in conjunction with prismatic joints. The NOVEMOR PROJECT [38] showed certain optimization tools could be developed to judge the parameters of a morphing wing. Gaspari et al. presented an optimal network for estimation of the camber, by combining genetic algorithms, modeling, and geometrical representation. For obtaining a more complete estimation of the aerodynamic work done and an overall energy model for morphing wings, Hwoong et al. [41] created a model with a simple spring system. These newer systems were also used in an attempt to make subsonic high altitude flight models. In an attempt to minimize drag production rates and the required actuation energy. Botez et al. [43] showed the numerical analysis of a wing section, originally based on the airfoil shape of the ATR 42, and the effective testing of two models, and a third morphing wing section from the same original airfoil, to be tested specifically for speeds below Mach 0.1 and an angle of attack of equal to or less than 0.1° . Wu et al. [44] formulated a method for the creation and optimization of a morphing wing with 2 steady states using an immune genetic algorithm (IGA). The system could provide an optimal solution due to the function of vaccination and immune selection in IGA. The conception of IGA is embedded in the optimization process of the new method, represented in the red box. Kai et al. [47] showed a different method for better shape approximation using rigid-body topologies.

Figure 4: Optimization Control as Described in [45].

Assembly

Morphing structures and surfaces are no exception to the bounds of low tolerances and critical activity. The eventual product must be under general aviation safety parameters and compliant with the design specifications [48]. Wing structures generally embody the largest number of components in an aircraft: ribs, spars, panels, clips, doublers, and

stringers [49]. Bi actuator systems are common albeit, the number, nature, and permutations of components used cannot be generalized. Each system can be expected to contain:

- An adaptive skin
- Fiber optic networks
- An actuator system
- A sensor system
- Power transmission

Figure 5: CAD Representation of the Wing Structure.

The wing box was made with a fully integrated fiber-optic system for detecting its structural health. The adaptive leading edge was made for improving take-off and landing performance as an alternative to conventional mechanical slats [51]. The trailing edge would be used for changing the camber in flight, to compensate with weight reduction related to the fuel consumption with its movement driven by equidistributed actuator configurations [52]. The adaptive trailing edge of the winglet helps with the load distribution over the wing and balanced gusts effect [53]. Fig (8) and fig (9) show a pictorial representation and schematic diagrams respectively.

Figure 6: Schematic of an Adaptive Wing [50].

Wing box

For testing a wing box in a wind tunnel [50] took extra measures by taking care to manufacture components which were resistant to any mishaps during the testing. It was also necessary to support the adaptive parts and it needed to be rigid

enough to disallow coupling and deformation under aerodynamic loads. By applying the said considerations to the ribs, panels and the wingtip's trailing edge, the main components of the wing box can be listed as two fiber-optic networks, multiple ribs running longitudinally from the dropping leading edge to the morphing trailing edge; top and bottom panels along with front and rear spars. The outer skin materials may vary from fixed to adaptable to SMA.

Leading edge

Consisting of a fiberglass structure that was highly deformable under external forces, the leading edge was connected by ribs, whose movement would produce the necessary actuation. The movement of the ribs was controlled by a motor through shafts. This specific arrangement was placed between the top and bottom panels of the wing box and its front spar caps and another line of joints between the web of two and a half spars where each was associated with the wing box and the leading edge respectively. There is no interference between the shape-changing portion and the fixed parts of the wing box. But the morphing leading-edge system could not be extended across the whole wing's surface due to complications in space and the machinery of the morphing wingtip.

Trailing edge

The main driving force was derived from transmission kinematics linked with actuators. This new architecture, consisting of dedicated motors and other embedded active systems could be completely allocated into the morphing section at a reasonable expense and maintenance cost. Another advantage of fitting the whole system into the morphing part is that the system will either work as a whole or fail completely. However, the probability of a single actuator failing alone is much higher than that of ten of them failing together. Also, by using such a multi-motor configuration, variable values of camber can be achieved along the wing, latitudinally, thereby providing a wing twist. The adaptive trailing edge increased efficiency by providing optimum trim and simultaneously weighing less, thereby reducing the required fuel.

Figure 7: Trailing Edge Mechanism [50].

Wingtip

The morphing wingtip structure consisted of a traditional wingtip with its trailing edge acting as a tab, with all the devices associated with the movement of the tab embedded into the structure similar to a flap. In all, the structure consisted of an elastic link between the moving part and the rigid system, motor, shaft, and a deformable structure. The deforming part of the structure is excited through cables which in real-life applications would be difficult to house inside the wing. The LE consisting of anti-icing and leading-edge morphing systems while the TE has only the morphing mechanism but has little to no room left. The adaptive winglet is designed to achieve load distribution and gust effects attenuation but if the electronics are all housed in the wingtip itself it could lead to undesired aero elastic behavior. In addition, the winglet could also be used as a directional control surface, alleviating the rudder efforts.

FUTURE

A morphing rudder's mechanism and development could soon be found, mainly for larger aircraft complete with additive manufacturing processes and orthotropic panels however, the testing phase provided uncertain results [54]. NASA and the Massachusetts Institute of Technology have recently presented 'MadCat'. It consists of thousands of small triangular blocks combined into a lattice-like structure for wing morphing. These blocks can build and rebuild an object giving it new shapes for specific tasks at any time. NASA and MIT developed a technology of composite injection molding in which the casting of one block takes 17 seconds instead of the previously needed several minutes. This easily scalable project is still far from the stage of industrial production but there have been tests of center equipped wings to monitor the airflow around the wing and continuously adjust its shape.

CONCLUSIONS

In this paper, different methods for controlling a morphing system and their assembly were discussed. Bi - actuator concepts integrated with a top surface made flexible by using a smart material for deformation seems like the most viable option and is being considered for further development. An only trailing edge morphing configuration would also find good use in flight operations. Although many concepts have been described above, only a handful of them were implemented on aircraft. Quite a few concepts for using morphing concepts on low-speed aircraft were conceived, but none were tested in flight. Since actuation systems can be bulky, any morphing system needs to overcome the barrier of weight. For low-speed aircraft, any such system should undergo a substantial change for any noticeable improvement in the aerodynamic properties while also being under the weight limit. For a successful conceptual design, it is important to have integrated and distributed actuators to avoid transmission mechanisms and using advanced light-weight composites for the fixed structure and the skin.

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