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Enabling Concepts and Technologies for Out-Of-Plane Morphing Wing Structure: A Review

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ABSTRACT

Background: Transforming the wing out of its original plane in general involves three main shape parameters; twist, span-wise bending, and chord-wise bending. Aerodynamic and dynamic behaviors resulting from out-of-plane transformation are significant and efforts to develop an actuation system that can deliver the actuation authority required are a multi-disciplinary challenge. The recent interest in the development of air vehicle with better control authority, maneuverability and longer flight endurance has revealed a need for a more thorough comprehension of the concept and structure of morphing wing. In response to this need, a review of morphing methods and enabling technologies of out-of-plane wings is presented.

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INTRODUCTION

A major objective of aeronautical engineering is to improve the efficiency and performance of existing air vehicles or to design new air vehicles with better efficiency than their predecessors by means of optimizing its aerodynamic, dynamic and structural layout of the air vehicles. One concept that has been adopted since the Wright Flyer is by altering the wing's configuration e.g. wing surface area to expand the optimal flight regime and this idea of changing the wing shape or geometry is known as morphing.

There is no definite definition of morphing wing concept, however most technical publications known to the author have come to a consensus that morphing wing allude to continuous shape change. However the conventional hinged control surfaces or high lift devices, such as flaps or slats that provide discrete geometry changes cannot be considered as ‘‘morphing” (Wlezien *et al.*, 1998).

Often time conventional air vehicle with conventional hinged control surfaces suffers from drag penalty and heavy noise due to open gaps and discontinuities in the surface during deployment. Thus, the wing operation may lead to decrease in aircraft’s endurance (Ifju *et al.*, 2002). Continuous reshaping the wing allows the airflow in each part of the air vehicle mission profile to be optimized and hence a maximum aerodynamic advantage (maximum lift/drag ratio), enlarged flight envelope and increased maneuverability can be achieved.

The apparent complexity of variable-geometry air vehicle has led several researchers exploring the ideal morphing actuation system. The morphing system offers minimum penalties due to additional weight, complex configuration and power required. Morphing structure also witnesses the integration of smart structures into morphing wing. In order to reach a fully-fledged morphing technology, a strong urge must be made to study at some of the aerodynamic and dynamic issues associated with shape change.

This paper intends to review the methods and enabling technologies of the selected out-of-plane morphing-wing designs with particular reference to the smart material utilized in out-of-plane morphing. The review gives the actual description of the previous morphing works.

Morphing Wing Classification:

The wing morphing concepts have been classified into three major types, as presented in Figure 1: planform alteration, out-of-plane, and airfoil adjustment. This classification follows a similar classification (Sofla, Meguid, Tan, & Yeo, 2010).

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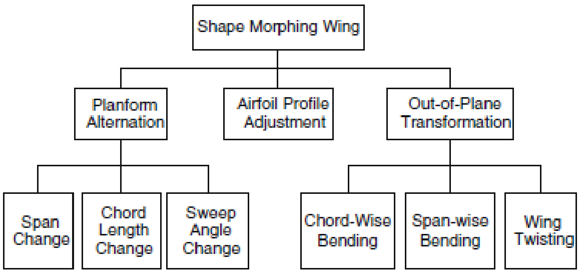


Fig. 1: A classification for shape morphing of wing (Sofla *et al*., 2010).

Morphing the wing out of its original plane is mainly involved three geometrical parameters: twist, dihedral/gull, and spanwise bending. The following text covers the previous works of twist, dihedral/gull, and spanwise morphing structure.

Enabling Methods Technologies:

This section discusses the different approaches, structural system and enabling technologies of out-of-plane morphing with respect to the shape parameters (twist, dihedral/gull bending and chordwise bending). The review has been categorized based on spanwise and dihedral/gull morphing.

Twist morphing:

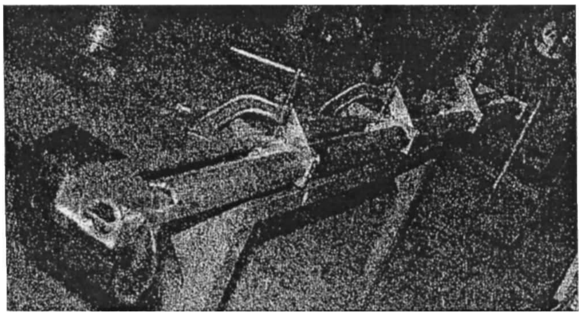
Generating wing twist for air vehicle can easily be achieved using standard actuation schemes such as connecting parts of the wing to a servo in the fuselage and embedding torque rods into the structure or using smart material method such Shape Memory Alloy (SMA) and Piezoelectric. Such an example of twist morphing is given by (Guiler & Huebsch, 2005). They implemented wing twisting morphing by utilizing a carbon actuator rod and a geared high torque servo in the leading edge to initiate morphing of a swept wing tailless aircraft in order to improve flight control.

In an alternate approach, (Garcia, Abdulrahim, & Lind, 2003) numerically analyzed the MAV engaged in a rolling maneuver by twisting its flexible membrane wing which was done using torque rods actuated by a single servomotor. The morphing actuator had forced the wing into an asymmetric wing twist. Similar analysis of MAV engaging in a rolling maneuver by twisting its flexible membrane wing was also conducted by (Stanford, Abdulrahim, Lind, & Ifju, 2007) at which they used vortex-lattice code, and an algorithm to obtain an optimized design. In another study, (Abdulrahim, Garcia, & Lind, 2005) employed similar MAV model and morphing method to analyze the flight characteristics associated with turn and spin.

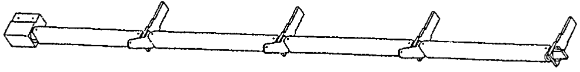
(Chekkal, Cheung, Wales, & Cooper, 2014) developed the adaptive wing-tip concept which can control the cant angle orientation, camber and twist throughout the flight envelope. In order to determine the aerodynamic forces and resulting loads, they executed a CFD numerical simulation on a morphing chiral wing-tip device applied to a regional jet type. (Majji, Rediniotis, & Junkins, 2008) performed a wind tunnel experiment using a novel morphing wing consists of an elastic structure (ABS plastic material) and is covered with an elastomeric skin in order to study the morphing wing aerodynamic response. The wing was rigidly coupled to four telescoping tubes, which were independently attached to the wing at four locations along the span. The tubes were connected to servomotors at the wing root which operated to twist corresponding sections along the span.

Similarly, (Chen *et al*., 2000) developed the Variable Stiffness Spar (VSS) concept to vary the torsional stiffness of the wing and enhance maneuverability (roll maneuver) of the existing F/A-18 PRM aircraft. Variable stiffness spar(s) (VSS) is an adaptive-structural concept which exploits the wing flexibility by varying the control surfaces and the structural stiffness to achieve the required maneuver performance during flight. The VSS which inspired by smart stiffness concept by (Griffin & Hopkins, 1995), can also deliver time-varying stiffness for active dynamic load control. Their VSS concept consisted of a segmented spar having articulated joints at the connections with the wing ribs and an electrical actuator capable of rotating the spar through 90 degrees. The segments of the spar were uncoupled when the orientation of the joints was horizontal, and the spar offered no bending stiffness. The segments join were completely continuous in the vertical position, and the spar provided the maximum torsional and bending stiffness. The VSS mechanism replaced the shear web of the existing spar, and it was completely contained within the wing. Figure 2a and 2b present the VSS actual mechanism built and schematic diagram respectively.

(Nam *et al*., 2000) propelled the VSS concept forward with the development of the torsion-free wing concept which proposed to attain a post-reversal aeroelastic amplification of wing twist. The primary structure of the torsion free wing consists of two main parts. The first is a narrow wing-box tightly attached to the upper and lower wing skin in order to provide the basic wing torsional stiffness. The second part consists of two variable stiffness spars placed near the leading and trailing edges, passing through all the rib holes. (Florance *et al*., 2004) took the use of the VSS concept a step further by exploiting the wing flexibility and improving the aerodynamic performance of the vehicle. Their wing incorporated a spar with a rectangular cross-section that runs from the wing root up to 58% of the overall wing semi- span. The spar is used to change the wing bending and torsional stiffness as it is rotated between its vertical and horizontal positions.



a) VSS mechanism



b) VSS schematic diagram

Fig. 2: Variable stiffness spar (VSS) mechanism (Chen *et al*., 2000).

Span wise bending (gull/dihedral):

It has been long-standing goal of air vehicle designers to vary the dihedral angle and change in gull configuration of the wing which is inspired by avian morphological changes for different flight regimes. Most gull designs work by dividing the wing into two hinged joined section that deflect in opposite directions to achieve gull configuration.

Multiple winglets concept is probably the most non-trivial concept for varying the dihedral angle wingtips where the split wingtips of a flying wing were folded symmetrically or unsymmetrically to achieve longitudinal and/or lateral/directional control. (Shelton, Tomar, Prasad, Smith, & Komerath, 2006)investigated the employment of the active multiple winglets concept on the U.S. Marine Corps Dragon Eye UAV using an aerodynamic panel code and active control simulation to optimize the winglet configuration and to evaluate its maneuvering flight performance. (Bourdin, Gatto, & Friswell, 2007), (Bourdin, Gatto, & Friswell, 2010) also investigated this concept at which they utilized a pair of winglets with adaptive cant angle by mounting them at the tips of a flying wing and actuated independently to investigate the use of variable-cant angle winglets for morphing aircraft control.

(Manzo & Garcia, 2010) analyzed the aerodynamic properties of a furled and a planar (rigid) hyper elliptic cambered span (HECS) wings and compared them to an elliptical rigid wing. The wing which imitated a furled HECS profile consisted of five segments across the span. The shape morphing of the HECS wing was achieved using individual shape memory alloy SMA-actuated segments that were powered in tandem from a central microcontroller.

(Supekar, 2007) developed a two-segment telescopic morphing wing for a UAV with adjustable span and gull angles using a servomotor and bell-crank arrangement to control the gull angle, whereas the outer wing allowed an increase in span. The aerodynamic analysis is successfully performed using Athena Vortex Lattice (AVL) code.

Chord wise bending (camber/airfoil adjustment):

The change of the effective curvature of the airfoil by means of actuators is the most investigated approach of wing morphing. Changing both chord and span camber uniformly along the span which are similar to the rotation of the ailerons can produce controllable twisting moment and thus enabling the entire wing to act as a unique control surface. Some wing camber researches only focus on changing certain parts (leading or trailing edge) which constitutes to the development of the mission adaptive wing (MAW) (Gilbert, 1981), (SMITH & NELSON, 1988), the active adaptive camber wing (AACW) (Ricci & Terraneo, 2005), and more recently, the mission adaptive compliant wing (MAC-Wing) concept (Hetrick, Osborn, Kota, Flick, & Paul, 2007). Numerous mechanisms or actuators have been explored and tested in reconfiguring the internal structure or reshaping the wing skin, such as shape memory alloy (SMAs), piezoelectrics, rubber muscle actuators (RMAs), electromagnetic magnetostrictive materials, etc.

Shape memory alloys (SMAs) are utilized as an actuator device and one of the smart materials which capable of producing substantial deformations compare to piezoelectrics and electrostrictives as shown in Table 1 (Bar-Cohen, 2002). SMAs are thermomechanical materials consists of a mixture of nickel and titanium, which have unique thermal and mechanical properties that allow them to change shape when heated or cooled (Liang & Rogers, 1990). Figure 3 shows SMA springs developed by (Dong, Boming, & Jun, 2008)utilized as actuation device for the skin of an airfoil.

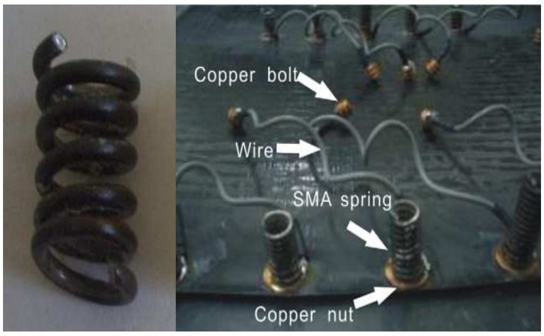


Fig. 3: SMA springs utilized on skin of an airfoil. (Dong *et al*., 2008).

Table 1: The characteristics of smart materials (Bar-Cohen, 2002).

Material	Max. strain (%)	Max. stress (MPa)	Elastic energy density(J/g)	Max. effic. (%)	Relative speed
Electrostrictor					
Polymer P (VDF-TrFE)	4	15	0.17	-	Fast
Piezoelectric Ceramic (PZT)	0.2	110	0.013	>90	Fast
Single Crystal (PZN-PT)	1.7	131	0.13	>90	Fast
Polymer (PVDF)	0.1	4.8	0.0013	n/a	Fast
SMA (TiNi)	>5	>200	>15	<10	Slow

(Abdullah, Bil, & Watkins, 2009) investigated the aerodynamic effects of changing the airfoil camber using SMAs to vary the shape of an airfoil to increase the L/D ratio throughout the flight regime of a UAV. A flexible material for the skin was also used for variable camber control. The aerodynamic effect of the position of the airfoil’s maximum camber and magnitude was analyzed using a modified panel method code. (Lyu & Martins, 2014) examined the aerodynamic performance benefits of a morphing trailing edge using the NASA Common Research Model (CRM) wing-body as the baseline geometry concept. The investigation was carried out using a high-fidelity aerodynamic model based on the Reynolds-averaged Navier–Stokes (RANS) and Spalart–Allmaras as the turbulence model.

More research and development has been done on smart-material actuation than the conventional actuation (electrical, hydraulic, pneumatic, etc). An example of widely prevailing smart-material in wing morphing is Macro-Fiber Composite (MFC) which has a sufficient actuator authority for shape control under aerodynamic loads. A MFC is a flexible, planar actuation device that consists of a layer of unidirectional piezoceramic fibers sandwiched between layers of copper electrodes and acrylic/Kapton (Wilkie *et al*., 2000). The layout MFC is presented in Figure 4. MFCs were developed at NASA Langley Research Center and numerous researches had focused on employing MFC as an actuator for structural control. An experimental wing model with six MFC patches on top surface is presented in Figure 5. Figure 6 depicts a fabricated aircraft employing MFC during actuation.

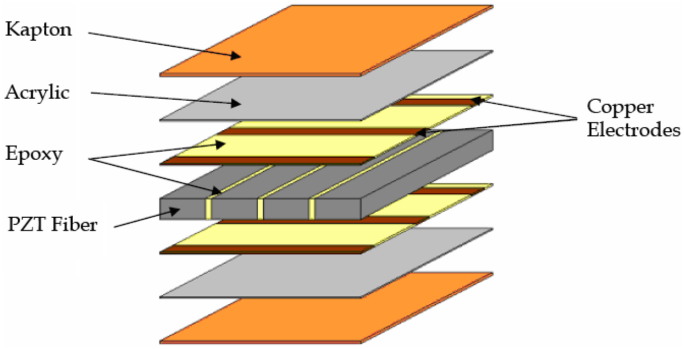


Fig. 4: Layout of macro-fiber composite (MFC) actuator (Onur Bilgen, Kochersberger, Diggs, Kurdila, & Inman, 2007).

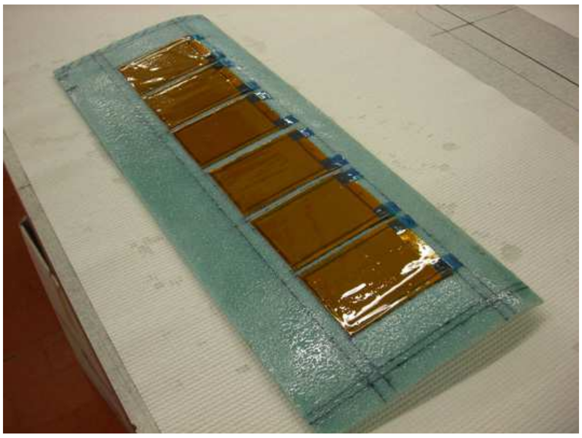


Fig. 5: Experimental wing model with MFC actuator (Paradies & Ciresa, 2009).

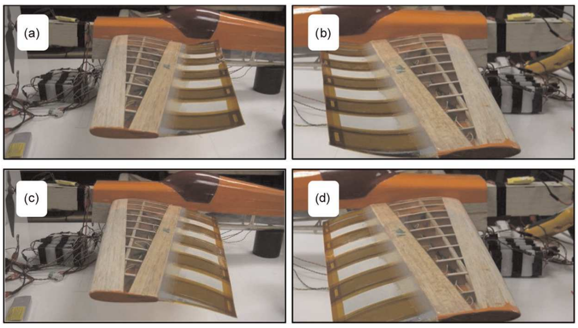


Fig. 6: Fabricated aircraft employing MFC during actuation (O. Bilgen *et al*., 2012).

Smart-material-based actuators have been widely used for camber changes. (Onur Bilgen, Kochersberger, Inman, & Ohanian III, 2010)and (Onur Bilgen, Kochersberger, Inman, & Ohanian, 2010) adopted piezoceramic composite called Macro-Fiber Composite (MFC) as the actuation element for a bi-directional variable camber thin airfoil to examine its two-dimensional aerodynamic coefficients. The study focused on response characterization under aerodynamic loads for circular-arc airfoils. The concept consisted of two MFC actuated thin bimorph airfoils and four pins are bonded to the airfoil at 5% and 50% of the chord from the leading edge. The variable pinned boundary conditions allow smooth deformation in both directions from a flat camber line.

(Kota *et al*., 2006) described the flight testing results of the Mission Adaptive Compliant Wing (MACW) adaptive structure trailing-edge flap used in conjunction with a natural laminar flow airfoil. The adaptive structure trailing-edge flap system was refined to augment the laminar boundary layer extent over a broad lift coefficient range for a high-altitude and endurance aircraft applications. The MACW model test flights were performed using the Scaled Composites White Knight aircraft at full-scale dynamic pressure, full-scale Mach number, and reduced-scale Reynolds numbers.

(Marques, Gamboa, & Andrade, 2009) evaluated the effect of the variable camber flap on lift and drag of a low speed UAV between its stall and cruise speeds and presented the aerodynamic optimization of the flap parameters. The actuation system of the variable camber flap consisted of two pins on each aluminium flap track and they were located at each tip of the 0.8m span model. The variable camber flap model employed the conventional electromechanical system and was fabricated with a GFRP (glass fibre reinforced plastic) skin and a light foam core. (Paradies & Ciresa, 2009) designed an active composite sandwich wing for a UAV with a thin profile and piezoelectric for roll control by implementing MFCs as actuators. The design model has seven integrated MFC elements (six MFCs on the upper surface of the wing and one MFC on the lower surface close to the wing root with a wing span of 500 mm. Numerical analyses coupling the finite element method (FEM) and computational fluid dynamics (CFD) were performed to fully evaluate the aeroelastic behavior of the active wing, piezoelectric actuation forces and the strength analysis.

The 2010 Virginia Tech Wing Morphing Design Team developed remote controlled aircraft model employing piezoelectric materials (Macro-Fiber composites) as the control surface actuation to replace all the traditional servomotor-controlled surfaces. The MFC patches were attached to a thin, pliant substrate in a bimorph configuration to allow for maximum aileron deflection and the spar tube was made from a fiberglass/epoxy matrix. There were no rotating, moving, or multi-piece parts or mechanisms in the MFC-actuated control surfaces which made the aircraft model fully solid-state piezoelectric controlled. The remote controlled aircraft which was powered with a single Lithium polymer battery was flight-tested and under gone wind-tunnel tests in interest of determining the roll rate information (L Butt *et al*., 2010), (Lauren Butt *et al*., 2010)(O. Bilgen *et al*., 2012). (Yang, Han, & Lee, 2006) discussed the feasibility of controlling camber of an airfoil using SMA actuators. The variable camber wing was a symmetric wing with four pairs of the SMA wire actuators were attached on the bottom surfaces of the wings in the chord-wise. The wing had two tapered graphite/epoxy composite plates and a steel body direction.

The U.S. Air Force Research Laboratory designed and built Variable Camber Compliant Wing which had a two foot chord length and can actively re-contour the airfoil camber up to 6% in order to resemble several NACA airfoil shapes at low flight speed. The development process of was discussed by (Joo, Marks, & Zeintarski, 2015). The wing structure consisted of a rigid main spar, flexible ribs, a single piece non-stretchable composite skin and Compliant Mechanism Systems as the camber deformation actuator. Wind tunnel experiments and numerical analysis using the aerodynamic modeling program XFOIL were carried out to compare the performance of a flapped airfoil section and the camber changed airfoil. (Marks *et al*., 2015) presented the wind tunnel test results of the AFRL's Variable Camber Compliant wing. The wind tunnel experiment was conducted with the purpose of demonstrating the operation of the VCCW under aerodynamic load and determining the section lift coefficient which varied with the changed in wing section camber. In a different study, (Miller, Rumpfkeil, & Joo, 2015)presented results for a loosely-coupled fluid-structure interaction (FSI) of the AFRL's Variable Camber Compliant Wing (VCCW) using FUN3D to compute the aerodynamic flow field and Abaqus to calculate the structural deformation. The CFD simulations were run second-order accurate in space with the Spalart-Allmaras turbulence model with the flow was assumed to be steady-state and no tunnel or support structure interference. They implemented a fully3D unstructured tetrahedral mesh that contained 2.77 million nodes.

(Kaul & Nguyen, 2014) performed numerical simulations with OVERFLOW employing the Spalart-Allmaras turbulence model to study the effect of various Variable Camber Continuous Trailing Edge Flap (VCCTEF) settings on the lift and drag of a Generic Transport Model (GTM) wing cross-section at a span-wise location. They considered five VCCTEF configurations with varying camber in the flap region and compared its lift and drag with baseline configuration (no flap deflection). In addition to the VCCTEF aerodynamic analysis, (Nguyen *et al*., 2014) presented wind tunnel testing results of the VCCTEF to explore the desirable ability of the VCCTEF concept for improved cruise efficiency and drag minimization. The VCCTEF model was scaled at 10% of a softened Boeing 757-based GTM wing, constructed of woven fabric composites skin and extruded polystyrene foam core with half of the bending stiffness of the scaled baseline GTM wing stiffness for achieving a 10% wing tip deflection. The VCCTEF consisted of three chordwise camber segments and five spanwise flap segments for a total of 15 flap segments. The gaps in between the spanwise flap segments were covered using elastomeric material to create a continuous and smooth trailing edge. SMA hinge line torque rods were employed as actuation components to drive the first and second camber flap segments and electric drive for the third camber flap segment.

(Onur Bilgen, Landman, & Friswell, 2013) executed low Reynolds number wind-tunnel testing of a solid-state piezocomposite variable-camber wing which utilized surface-induced deformations with MFC actuators. The variable-camber wing was made up of a rigid (rapid-prototyped) internal spar structure and a partially-active shell which was actuated by10 sets of MFC bimorphs, laid in a non-uniform arrangement between the "root" and the "tip" of the wing along the spanwise direction. The top and bottom trailing edge surfaces were joined by a strip of externally adhered Kapton tape.

Conclusion:

This review has delved into out-of-plane morphing-wing which signalizes the concept as an emerging aerospace technology and continually evolving to expand their capabilities and effectiveness particularly in actuation methods and morphing structure. From this review, it is observed that camber morphing is the dominant research topic compare to other out-of-plane morphing methods notably dihedral/gull or spanwise bending morphing which are less researched upon even though successful flying tests have been performed. There is a growing interest in twist morphing as well because of the considerable effect it can deliver on the aerodynamic performance of a lifting surface.

As for actuation system, materials with variable stiffness such as shape memory alloy actuators (SMA), piezoelectric actuators (PZT) or shape memory polymers (SMP) have found their way into morphing research since these materials offer the best weight advantage and versatility that expand morphing concepts and capabilities in previously beyond the bounds of possibility. However the piezoelectric actuators do not have an innate capacity to provide acceptable roll control for air vehicles and thus fail to deliver the actuation authority required.

One can note the employment of elastomers matrix composites which has the ability to undergo large elastic deformations without permanent changes in shape as the morphing skin.

Another trend in out-of-plane morphing is the advent of a novel adaptive Variable Camber Compliant Wing (VCCW) that can actively re-contour the airfoil camber using compliant mechanisms. The VCCW provides greater shape control of the entire airfoil and a continuous contour to reduce drag.

It is apparent that the integration of smart-material into actuation system has propelled morphing wing into an advance stage, even producing a successful flying test bed mainly in enabling technologies.

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