Journal of
Intelligent Material
Systems and Structures

Review Article

Journal of Intelligent Material Systems and Structures
1–24

DOI: 10.1177/1045389X16629569
jim.sagepub.com
SAGE

Morphing aircraft based on smart materials and structures: A state-of-the-art review

Jian Sun[1], Qinghua Guan[1], Yanju Liu[2] and Jinsong Leng[1]

Abstract
A traditional aircraft is optimized for only one or two flight conditions, not for the entire flight envelope. In contrast, the wings of a bird can be reshaped to provide optimal performance at all flight conditions. Any change in an aircraft's configuration, in particular the wings, affects the aerodynamic performance, and optimal configurations can be obtained for each flight condition. Morphing technologies offer aerodynamic benefits for an aircraft over a wide range of flight conditions. The advantages of a morphing aircraft are based on an assumption that the additional weight of the morphing components is acceptable. Traditional mechanical and hydraulic systems are not considered good choices for morphing aircraft. "Smart" materials and structures have the advantages of high energy density, ease of control, variable stiffness, and the ability to tolerate large amounts of strain. These characteristics offer researchers and designers new possibilities for designing morphing aircraft. In this article, recent developments in the application of smart materials and structures to morphing aircraft are reviewed. Specifically, four categories of applications are discussed: actuators, sensors, controllers, and structures.

Keywords
smart materials and structures, morphing aircraft, review

Introduction

The kite, which might be considered the earliest type of aircraft, was invented by the Chinese 2000 years ago. These kites were made from easily obtained natural materials: silk fabric or paper for the wings, fine, high-tensile-strength silk for the tether, and bamboo for a strong, lightweight airframe. The first rocket was developed in the 13th century in China using black powder as the propellant. The rocket was the first powered aircraft used in war and was the forerunner of the jet engine. The Wright brothers completed the first flight of a powered, manned aircraft (the *Wright Flyer*) on 17 December 1903. The 274 kg aircraft had two 12.3 m wings and was powered by an 8.9 kW, 82 kg engine. The *Wright Flyer* stimulated the rapid development of aircraft in the 20th century.

To improve aerodynamic performance, the use of bionics in aircraft design is being considered. Swifts control their glide performance by changing the geometry of their wings; for example, they adjust their wing sweep to suit the speed (Lentink et al., 2007). Jackdaws (Rosén and Hedenström, 2001) and other birds (Thomas, 1996) maneuver in flight by changing the geometry of their wings and tail. It follows that morphing wings can play a very important role in aircraft design (Cistone, 2004; Weiss, 2003).

A number of aircraft with morphing wings have been designed and produced since World War II, including the X5 (sweep wing, USA, 1951–1958), the F-111 (sweep wing, USA, 1964–2010), the XB-70 (span bending wing, USA, 1964–1969), the SU-17 (sweep wing, former Soviet Union, 1966-till date), the MIG-23 (sweep wing, former Soviet Union, 1967-till date), the SU-24 (sweep wing, former Soviet Union, 1967-till date), the Tu-22M (sweep wing, former Soviet Union, 1969-till date), the F-14 (sweep wing, USA, 1970–2006), the B-1 (sweep wing, USA, 1974-till date), the Tornado (sweep wing, UK, Germany, and Italy, 1974-till date), and the Tu-160 (sweep wing, former Soviet

[1]Centre for Composite Materials and Structures, Science Park of Harbin Institute of Technology (HIT), Harbin, People's Republic of China
[2]Department of Astronautical Science and Mechanics, Harbin Institute of Technology (HIT), Harbin, People's Republic of China

Corresponding author:
Jinsong Leng, Centre for Composite Materials and Structures, Science Park of Harbin Institute of Technology (HIT), P.O. Box 3011, No. 2 YiKuang Street, Harbin 150080, People's Republic of China.
Email: lengjs@hit.edu.cn

Union, 1981-till date) (Barbarino et al., 2011a). The most famous example is the Grumman F-14 Tomcat. This aircraft, which was featured in the film "The Final Countdown," was in service with the US Navy from 1974 to 2006. The wing structure was made of titanium, including the wing box, the wing pivots, and the wing skins. The F-14's wing sweep could be varied between 20° and 68° in flight to obtain the optimum lift-to-drag ratio for the Mach number. This aircraft was retired by the US Navy on 22 September 2006. The main reasons given for the F-14's retirement were the high number of maintenance hours and the high costs resulting from the heavy and complex sweep wing structure.

To overcome the problems with traditional materials and structures, novel materials are required (Donadon and Iannucci, 2014; Lloyd, 2007). Smart materials and structures, which offer self-actuating, self-sensing, self-healing, self-assembly, and self-adaptive capabilities, have great potential for applications in morphing aircraft (Rodriguez, 2007; Simpson et al., 1998). A variety of morphing technologies based on smart materials and structures will be required to enable an aircraft to perform in-flight configuration changes for optimum performance (Colozza, 2007; NASA, 2001; Website).

Smart materials and structures

It is difficult to define "smart" materials. Unlike static, or "dead," materials, smart materials are "alive": they can respond to changes in the environment (Bhavsar et al., 2008; Tzou et al., 2004). Therefore, smart materials are not only structural materials but also active materials. Sources of stimulation include stress, strain, electricity, magnetism, heat, light, and microwave radiation (Bogue, 2012). Currently, piezoelectric, magnetostrictive, and ferroelectric materials, optical fibers, electrorheological and magnetorheological fluids, shape memory alloys, shape memory polymers, electro-active polymers, and multifunctional nano-composites can be considered smart materials (Sater and Crowe, 2000; Vessonen, 2002). Smart structures include auxetic honeycombs, variable-stiffness tubes, multi-stable structures, and corrugated structures. In general, smart materials and structures comprise a smart system. To draw an analogy to humans, as shown in Figure 1, smart materials and structures can obtain information from the environment around the skin (sensing), they then produce an internal chemical or physical effect delivered to the brain for decision making (control), and finally, they implement actions through the muscles (actuation). The information passes through the nerves, and each part is linked by tendons and fibrous bands (structures).

Smart materials and structures have one or more of the three main features as follows:

1. Self-actuating—the system produces an output such as force, displacement, heat, and light after being stimulated (Chung, 2004; Kang et al., 2006; Krstulovic-Opara et al., 2003; Song et al., 2011b).
2. Self-sensing—in response to changes in the environment, the system can generate electric or magnetic signals or undergo strain that can be measured to describe the environment (Kruusamäe et al., 2011; Moslehi et al., 2011; Sodano et al., 2004).
3. Self-adaptive—the system can change its geometry to adapt to the environment (this feature applies specifically to structures) (Rodrigues et al., 2010; Vos et al., 2011a, 2011b).

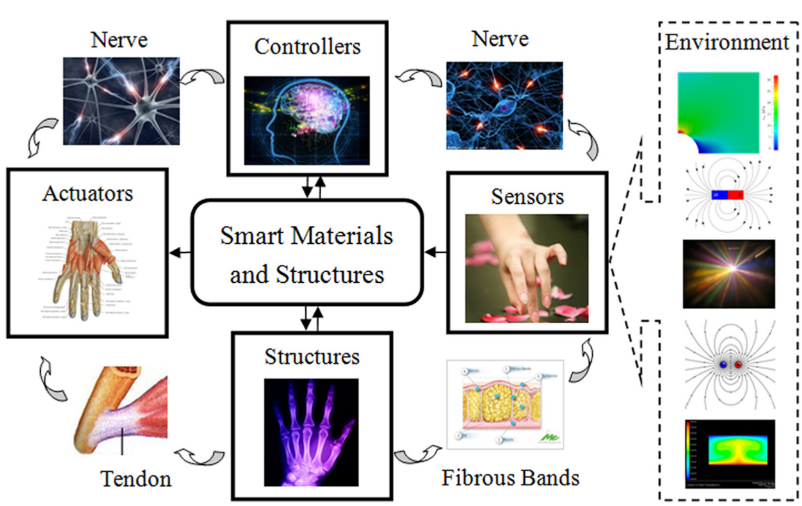

Figure 1. Smart materials and structures.

Table 1. Properties of typical smart materials.

Unit or method	Density g/cm^3	Nominal stress MPa	Strain %	Actuation frequency	Stimulation S	E	M	T
Shape memory alloy (SMA) (Hartl and Lagoudas, 2007; Nespoli et al., 2010; Wei and Sandström, 1998)	6.4–6.5	400–700	8	Slow		•		•
Piezoelectric ceramic (Craig, 1996; MEMSnet, 2014; Website)	7.5–7.8	100	0.1	Fast	•	•		
Piezoelectric composites (Bent and Pizzochero, 2000; Smart Material Corp., 2014; Website)	3.79	34–41	1.5	Fast	•	•		
Shape memory polymer (SMP) (Leng et al., 2011; Liu et al., 2009, 2014)	0.92	2–10	50–100	Slow	•	•	•	•
Elastic-active polymer (EAP) (Bar-Cohen, 2002; Shahinpoor et al., 1998)	1–2.5	10–30	300	Fast	•	•		
Magnetostriction (Bar-Cohen, 2000)	9.2	100	2	Fast	•		•	
Electrorheological fluids (ER) (Hao, 2001)	>	0.016	N/A	Fast	•	•		
Magnetorheological fluids (MR) (Kciuk and Turczyn, 2006; Park et al., 2010)	3–4	0.05–0.1	N/A	Fast	•		•	

Here, "S" denotes nominal stress and strain, "E" denotes electric, "M" denotes magnetic, and "T" denotes temperature.

Table 1 presents the properties and the means of stimulation for various common smart materials. Generally, smart materials have a high energy density (Tieck et al., 2004). According to the requirements of a particular application (e.g. stress, strain, weight, speed), designers can select the best material.

Morphing aircraft

The basic principle of an airplane can be described as follows: gravity is overcome by the lift generated by the flow of air over the aircraft's wings, and the lift depends on the wing shape and size and the velocity of the aircraft. Drag can be balanced by thrust. In one sense, for a given airplane fuselage, or body, the aerodynamic performance depends on the wing configuration. For a given thrust and airspeed, there will be an optimal wing configuration for each mission (Joshi et al., 2004) (Figure 2).

The degree of morphing in a wing can be classified as large, medium, or small (Gomez and Garcia, 2011; Jacob and Smith, 2009; Sofla et al., 2010) depending on the dimension that varies. Folding wings, variable-sweep wings, variable-span (telescoping) wings, and deployable wings comprise the large category. Twisting wing, flexible winglets, variable-chord (telescoping) wings, and variable-camber wings comprise the medium category. Variable-airfoil wings and bulging wings comprise the small category. Aircraft with morphing technologies has some advantages over fixed-geometry aircraft, and these advantages are listed in Table 2. A multi-mission aircraft can be designed for good performance in multiple flight conditions. For example, a fighter with folding wings or variable-sweep wings can have good performance at both high speed and low speeds, which can reduce fuel consumption and improve the flight envelope dramatically. Aircraft with variable-chord or variable-camber wings can have shorter takeoff distances. Variable-span wings, flexible winglets, and twisting wings can improve the aerodynamic performance of low-speed aircraft.

Different levels of morphing require diverse types of materials and structures to meet its various demands. Some of the earliest research on smart materials and structures for morphing aircraft mainly focused on medium morphing, such as the research conducted by the Massachusetts Institute of Technology (Spangler, 1989). In that research, a helicopter rotor blade trailing-edge flap was actuated by piezoelectric materials to control the aerodynamic force. In the 1990s, several types of smart materials and structures were investigated, including piezoelectric materials, electrostrictive materials, magnetostrictive materials, shape memory alloys, and fiber optic sensors (McGowan et al., 1999; Martin et al., 1998). Several studies have focused on morphing rotor structures using piezoelectric materials (Barrett, 1996; Barrett et al., 1998; Barrett and Stutts, 1997; Ehlers and Weisshaar, 1990; Giurgiutiu et al., 1994; Rodgers et al., 1997; Steadman et al., 1994), shape memory alloys (Roglin et al., 1994; Roglin and Hanagud, 1996), and magnetostrictive materials (Giurgiutiu et al., 1995). Piezoelectric actuators were used in morphing airfoil wings (Pinkerton and Moses, 1997) and in the control fins of a missile (Barrett and Stutts, 1998). Since the late 1990s, a large number of investigations on smart materials and structures for morphing aircraft have been conducted, and interest in the subject has been global (Barbarino et al., 2011a). Several studies have involved unmanned aerial vehicles (UAVs) (Baier and Datashvili, 2011; Daynes

Table 2. Advantages of morphing aircraft (Frommer and Crossley, 2005; Jha and Kudva, 2004; Previtali et al., 2014b; Roth et al., 2002).

Morphing methods		Advantages
Large	Folding	*Increase* the critical Mach number *Decrease* parasitic drag
	Sweep	*Increase* the critical Mach number *Decrease* high-speed drag
	Span telescoping	*Increase* L/D, loiter time, cruise distance *Decrease* engine requirements
	Deployable	*Increase* L/D, loiter time, cruise distance *Decrease* engine requirements
Medium	Twist	*Increase* maneuverability *Prevent* tip stall
	Winglet bending	*Increase* L/D, maneuverability *Decrease* induced (tip vortex) drag
	Chord telescoping	*Increase* low-speed airfoil performance
	Variable camber	*Increase* airfoil efficiency *Delay* separation
Small	Variable airfoil	*Increase* high-speed airfoil performance
	Bulging	*Increase* wing efficiency *Decrease* compressibility (wave) drag

Here, L/D means Lift to Drag ratio.

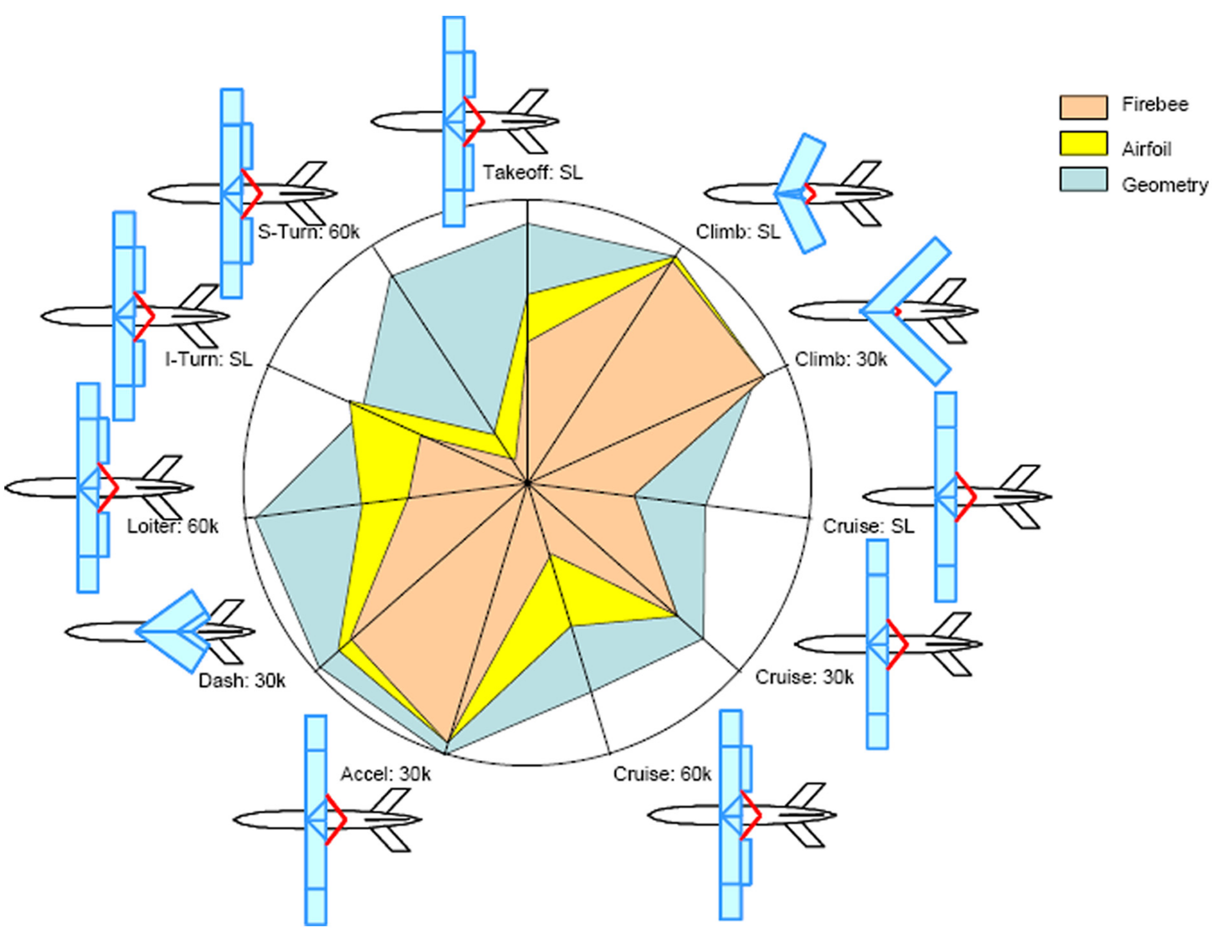

Figure 2. Comparing the predicted performance of a fixed-geometry wing, a morphing-airfoil wing, and a morphing wing for various missions (Joshi et al., 2004).

and Weaver, 2013a; Gomez and Garcia, 2011; Kuder et al., 2013; Kudva, 2004; Thill et al., 2008), and several mature morphing technologies for helicopter rotor blades and jet engines have already been flight-tested with full-scale test articles (Calkins and Mabe, 2010; Giurgiutiu, 2000b, 2011). In the next four sections, applications of smart materials and structures in morphing aircraft will be described in detail.

Actuators

Shape memory alloys

A shape memory alloy (SMA) is a metallic alloy such as NiTi, NiTiCu, and CuAlNi that can recover from a deformation and return to its original shape when subjected to heat (Otsuka and Wayman, 1998) which is known as shape memory effect. There is four transition points known as the martensitic start and finish temperatures (Ms and Mf) and the austenite start and finish temperatures (As and Af). Through a training cycle, an SMA acquires a stabilized strain that can be recovered when the temperature is higher than Ms. SMA has the property of super-elasticity, which means it could work even under high applied loads and large inelastic deformations, or undergo large strains without plastic deformation or failure (Barbarino et al., 2014). SMAs are very desirable for actuators because of properties such as high output forces, large recoverable strains, high energy densities, controllability, and the capability for one-way and two-way memory effects. SMAs are already widely used in aerospace morphing structures.

The most well-known application of SMAs is in an engine nozzle on a Boeing commercial airplane to reduce jet noise (Calkins et al., 2006). A large amount of theoretical work and simulations were performed by Texas A&M University and the Boeing Company (Hartl et al., 2010a, 2010b; Oehler et al., 2012a, 2012b). In August 2005, full-scale flight tests of variable-geometry chevrons, which were actuated using an SMA and installed on a 777-300ER with GE-115B engines, were completed (Mabe et al., 2007); photographs of the chevrons are shown in Figure 3. The results indicated that noise in cruise was significantly reduced. The chevrons improve the mixing of the freestream air and the fan stream. Other uses of SMA actuators in jet engines including a morphing inlet internal wall (Pitt et al., 2002), a morphing intake (Song et al., 2011a), and a morphing nozzle (Mabe, 2008) have also been investigated. The morphing inlet internal wall was tested in a wind tunnel.

SMA actuators can be used to alter the wing geometry as well. A variable-sweep wing controlled by SMA ribbons on the spar has been investigated (Galantai et al., 2012). In several other studies, SMA wire was used to create a morphing trailing edge to enhance lift (Kang et al., 2012; Karagiannis et al., 2014; Ko et al., 2014; Senthilkumar, 2012). Several segmented morphing trailing-edge concepts, which produce a larger trailing-edge angle, have been investigated (Ameduri et al., 2011; Barbarino et al., 2009b, 2011c; Wang et al., 2013). A similar approach can be used in the leading edge to increase the lift-to-drag ratio (Abdullah et al., 2011). Cornell University designed a Hyper-Elliptic Cambered Span (HECS) wing using SMA actuators (Manzo et al., 2005). This morphing wingtip can markedly improve maneuverability by enhancing yaw control while in the furled state. Groups of SMA actuators have been used to create a morphing-airfoil wing for subsonic cruise flight conditions (Brailovski et al., 2010; Georges et al., 2012), and wind tunnel tests showed

Figure 3. Full-scale flight tests of SMA-actuated variable-geometry chevrons on a Boeing 777-300ER with GE-115B engines (Mabe et al., 2007).

reductions in drag from 14.5% to 26.7% with an average value of 18.5% under quasi-constant lift conditions. SMA torque tube actuators have been used to provide near-optimum blade twist for helicopters in both hover and cruise flight conditions (Bushnell et al., 2008). SMA actuators have also been used in bionic flapping wings. An artificial beetle hind wing produced a flapping motion at 9 Hz with a 120° flapping angle using cyclic heating with two SMA wires (Muhammad et al., 2010).

Piezoelectric materials

A crystal with piezoelectric properties was discovered by the Curie brothers in 1880. A maximum of 0.1% strain can be obtained by applying a voltage to a piezoelectric material (Bogue, 2012; Vessonen, 2002). Layers of these crystals can be stacked to form a piezoelectric stack actuator. Piezoelectric fibers can be mixed with resin to produce piezoelectric composites. These composites can produce larger strains and various types of motion (e.g. extension, bending, and twisting). These composites are generally referred to as active fiber composite (AFC), macro fiber composite (MFC), or lightweight piezo-composite actuator (LIPCA).

Piezoelectric ceramics. Because piezoelectric ceramics are capable of producing large output forces and high-frequency responses, they have been used to drive hydraulic pumps. The principle of operation is as follows. A chamber with an inlet and an outlet is linked to a hydraulic system through one-way valves. The piezoelectric ceramic actuator moves a metal membrane to change the volume of the chamber cyclically according to a periodic voltage. Because of the pressure differential, the liquid flows from the inlet to the outlet (Chapman et al., 2005; Chaudhuri and Wereley, 2010; Kim and Wang, 2007; Oates et al., 2000; Sirohi and Chopra, 2002). These pumps have achieved maximum flow rates of 2300 cc/min and output pressures exceeding 200 bar in the stalled condition. A piezoelectric hydraulic pump was successfully used in a morphing wing on a remotely piloted vehicle (O'Neill and Burchfield, 2007).

Piezoelectric ceramics have also been used in linear actuators in helicopter rotor systems to improve vibration, noise, and aerodynamic performance (Straub et al., 2004a). An important technological advancement would be to increase the output of piezoelectric ceramic actuators (currently, the maximum extension strain is only 0.1%). Several different types of piezoelectric actuators such as the O type (Grohmann et al., 2006), the L-L type (Lee and Chopra, 2001), and the X type (Straub et al., 2004b) have been designed and tested. O-type actuators were used to drive trailing-edge flaps installed on MD900 rotor blades in whirl tower tests conducted by the Boeing Company. X-type actuators were successfully used in a BK117 S7045 prototype aircraft in Europe, as shown in Figure 4. The results showed that the vibrations were reduced as much as 90% (to less than 0.05 g) when the active-flap rotor was installed (Jaenker et al., 2008; Konstanzer et al., 2008).

Several researchers have designed piezoelectric actuators based on a "step and repeat" driving strategy which means actuators produce displacement pulses by insistently repeated motions to generate larger linear displacements and larger output forces (Loverich, 2004; Paine et al., 2008) to control the configuration of a morphing structure rapidly and accurately.

Piezoelectric composites. Piezoelectric composites have been used to reduce vibration and noise from helicopter rotors. At the German Aerospace Center (DLR), piezoelectric composites were integrated into rotor blades to control blade twist (Monner et al., 2011). Rotor blade trailing-edge flaps with piezoelectric composites actuators can achieve similar performance (Koratkar and Chopra, 2000).

In several studies, the camber of the wings of a micro air vehicle (MAV) was altered using piezoelectric composites to change the lift, the drag, and the pitching moment (Bilgen and Friswell, 2014; Heryawan et al., 2005, 2006; Molinari et al., 2015; Paradies and Ciresa, 2009; Prazenica et al., 2014) or to control the roll and pitch by morphing the trailing edge near the wingtips (Bilgen et al., 2007; Probst et al., 2012; Vos et al., 2007); the feasibility of these designs has been demonstrated in flight tests (see Figure 5). An MAV in which the elevators were controlled by piezoelectric composites was constructed and tested in a wind tunnel (Yoon et al., 2006a, 2006b). In a biomimetic approach, piezoelectric composites have been used to produce a flapping wing (Syaifuddin et al., 2005) that takes advantage of the high bandwidth of piezoelectric materials. In another study, the composites were installed in a flexible flapping wing to change the camber and increase the lift as much as 20.8% at 8 Hz flapping frequency, 20° pitch angles, and 10 m/s flow velocity (Kim et al., 2008).

Shape memory polymers

A shape memory polymer (SMP) is a type of polymer that, like an SMA, exhibits the shape memory effect. SMPs are capable of significant macroscopic recovery after receiving an external stimulus (e.g. heat, electricity, light, magnetism, microwaves, moisture, or a change in pH) (Leng et al., 2011). During this process, the material transitions between a glassy state, that is, hard, with a high Young's modulus (greater than 3 GPa), and an elastic state, that is, soft, with a low Young's modulus (1–10 MPa), so there is a distinct change in stiffness. Because of their low recovery forces,

Figure 4. BK117 S7045 flight test with active rotor trailing-edge flaps actuated by piezoelectric actuators (Konstanzer et al., 2008).

Figure 5. Micro air vehicle controlled by piezoelectric materials on the ground and in flight (Bilgen et al., 2007).

SMPs are frequently used as actuators in deployable space structures, that is, in a weightless environment (Leng et al., 2012; Liu et al., 2014). However, SMPs have great potential for applications requiring a morphing skin because of their variable stiffness. SMP morphing skins can withstand aerodynamic loads in the glassy state and tolerate large deformations (up to 100% strain) in the elastic state, and thus, they can accommodate morphing structures (McKnight and Henry, 2005; Sun et al., 2012).

SMP composites have been fabricated by mixing carbon fibers, glass fibers, or elastic fibers with an SMP resin, which enhances the mechanical performance of the SMP. Morphing skins based on SMP composites have been designed and tested in telescoping wings (Perkins et al., 2004; Reed et al., 2005; Yin et al., 2008), variable-camber wings (Sun et al., 2013, 2014b; Yin et al., 2009), sweep wings (Keihl et al., 2005; McKnight and Henry, 2008), deployable wings (Leng et al., 2015; Yu et al., 2009), and folding wings (Bye and McClure, 2007; Cantrell and Ifju, 2015). Figure 6 shows the deployment of a wing with a morphing skin. The SMP composite skin alters its shape when heated and maintains a smooth and seamless wing surface.

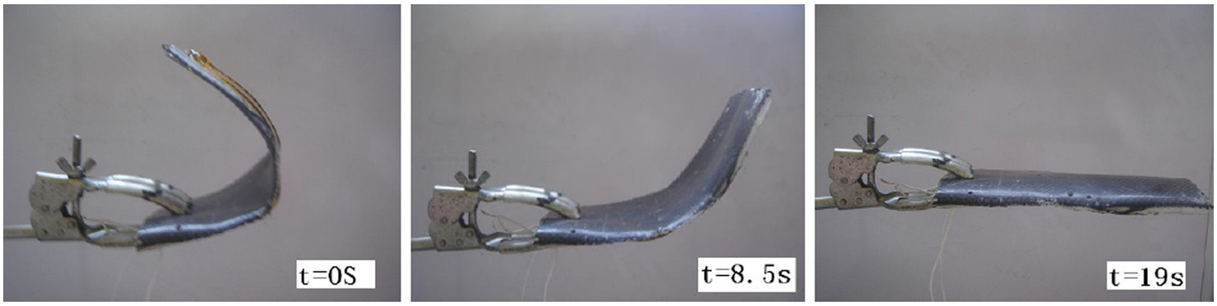

Figure 6. Deployable wing with SMP composite skin (Yu et al., 2009).

Figure 7. A lighter-than-air vehicle controlled with EAP actuators (Michel et al., 2007).

Electro-active polymers

An electro-active polymer (EAP) can be stimulated by electricity to produce a significant change in shape or size, where the strain can be as high as 300% (Bar-Cohen, 2002). EAP materials include dielectric elastomers (DE), ionic polymer–metal composites (IPMCs), polyvinylidene fluoride (PVDF), and other similar materials. As an actuator, EAPs have many advantages including low weight, low power consumption, a fast response, and flexibility (Zhao et al., 2015). EAPs have been used in flapping wing MAVs (Kim et al., 2007; Lee et al., 2006; Park et al., 2005). Only a 2.5–4 V sinusoidal signal was required to generate sufficient lift from the flapping wings for the MAV to become airborne. EAPs have also been used in actuators for the trailing edges of a fixed-wing UAV to increase the lift (Molinari et al., 2011). A small lighter-than-air vehicle whose rudders and elevators are controlled by EAP actuators is shown in Figure 7. The 3.5-m-long prototype vehicle was tested successfully in 2006 and in 2007 and demonstrated satisfactory control performance (Michel et al., 2007).

Magnetostriction

Magnetostriction is a property of certain materials in which the material undergoes a change in dimension or shape when subjected to a magnetic field. Terfenol-D (chemical composition: $Tb_{0.3}Dy_{0.7}Fe_{1.9}$) is a typical magnetostrictive material that undergoes a large induced strain in a low-intensity magnetic field at room temperature (Claeyssen et al., 2002). A linear step actuator based on Terfenol-D was demonstrated to have a very good performance: a maximum force of 410 N, a range of motion of 45 mm, a maximum speed of 60 mm/min, and 95 W of power. In comparison with conventional piezoelectric actuators, it could generate much higher actuation strains. It has higher actuation stresses in comparison with solenoid and moving-coil transducers (Kim and Sadighi, 2010). Magnetostrictive materials have been used to drive hydraulic pumps (Bridger et al., 2004; Chaudhuri et al., 2009; Sneed et al., 2007). The principle is similar to that of the piezoelectric pump. A maximum pressure of greater than 1700 lbf/in^2 was produced, and the output power reached 180 W. A design for a variable-span morphing wing UAV is shown in Figure 8.

At present, smart materials are mainly used as actuators. Comparing with conventional electromotor, smart materials have the properties of higher power density, more output force (SMA, piezoelectric materials, and magnetostriction materials), larger output displacement (SMP, EAP, and MFC), higher output frequency (piezoelectric materials, magnetostriction materials), or other features. The designers could choose them according to application conditions. However, it should be noted that there are still some shortcomings of smart materials. First, for SMA, piezoelectric materials, magnetostriction materials, and some other materials, closed-loop control is required to achieve the high precision control. Second, some materials need special power source to drive, which means the increasing in the complexity and weight of additional power source. For example, EAP, piezoelectric materials, and magnetostriction materials need to be driven by high voltage or high current. Third, high level of the demanding for driving energy makes it difficult to find an efficient method to drive some materials, such as SMP. Moreover, some materials have poor mechanical properties, which have restricted the

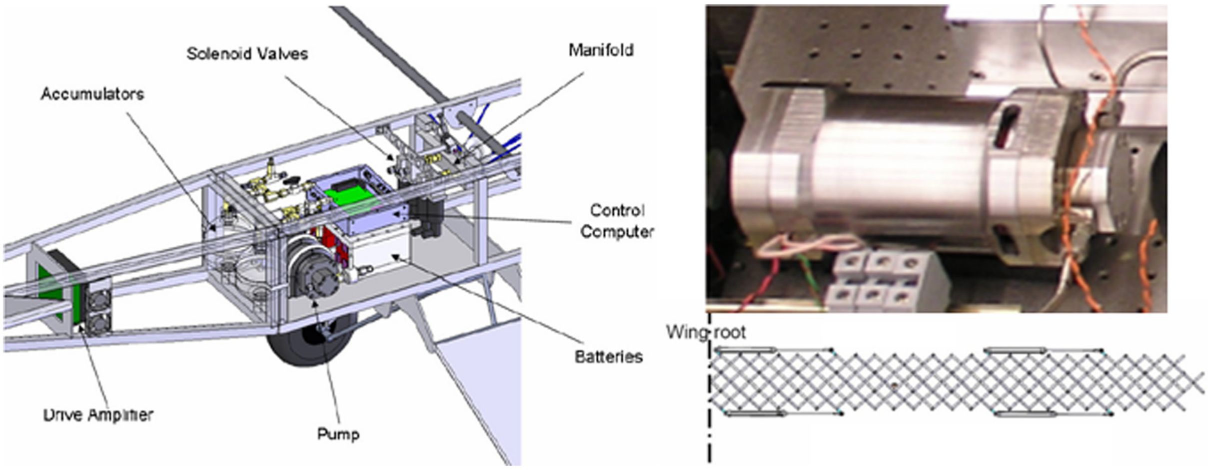

Figure 8. Hydraulic and control systems for a morphing wing UAV (Sneed et al., 2007).

development and application of them. For instance, piezoelectric materials and magnetostriction materials usually are partial to brittle failure and SMA, SMP, and EAP have poor anti-fatigue ability. All these aspects mentioned above should be avoided cautiously when applying these smart materials as actuators. Materials modification should be focused on in future work.

Sensors

Optical fibers

In a fiber Bragg grating (FBG) sensor, a grating is etched into the core of an optical fiber. The refractive index of the fiber will change in response to an axial strain or a change in temperature. Strain caused by changes in the ambient temperature, stress (Yi et al., 2012), pressure (Urban et al., 2010), or crack formation, among other factors, can be monitored by FBG sensors. The strain distribution can be obtained accurately by temperature compensation (Kim et al., 2013). Embedded FBG sensors have been used in composite wings to monitor impact damage (Nakamura et al., 2007; Takeda et al., 2007), cracks (Sekine et al., 2006), and loads (Costa et al., 2014). These sensors can identify the locations and the shapes of fatigue cracks and the time of failure. Furthermore, FBG sensors can monitor the dynamic strains in a wing in flight (Cusano et al., 2006; Lee et al., 2003). The wing root structure of an F/A-18 was tested under fatigue loading. Using FBG sensors, the fatigue life and mechanisms and the failure locations could be monitored (Davis et al., 2012; Schembri et al., 2013).

FBG sensors can be used in morphing wings to monitor the shape of the wing. Deflections in variable-camber wings (Figure 9) have been determined from the strain in a metal plate or a hinge measured using FBG sensors (Ciminello et al., 2013; Li et al., 2013a).

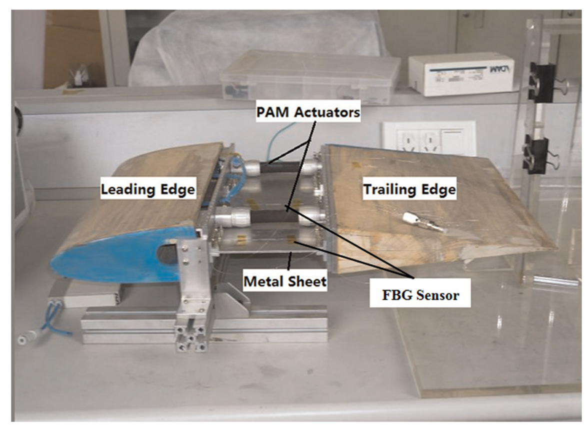

Figure 9. Model of a flexible, variable-camber wing (skin removed) monitored by an FBG sensor (Li et al., 2013a).

The actual shape of a twisting wing actuated by SMAs can be monitored with an array of FBG sensors and a neural network (Mieloszyk et al., 2011a, 2011b). The shape of an SMP can also be measured with FBG sensors, which have potential applications in a folding skin (Li et al., 2013b, 2013c).

Piezoelectric materials

In piezoelectric materials, applying an electric current to the material causes the material to undergo a change in dimensions. Conversely, a change in dimensions (such as by an applied mechanical stress) generates an electric charge in a piezoelectric material. This property can be used to create a sensor. Piezoelectric sensors can be installed inside a structure or attached to the surface to detect internal structural damage based on sound and ultrasound (Shang et al., 2008). In one study, a health monitoring system for a composite airframe (including the wings, the fuselage, and the empennage)

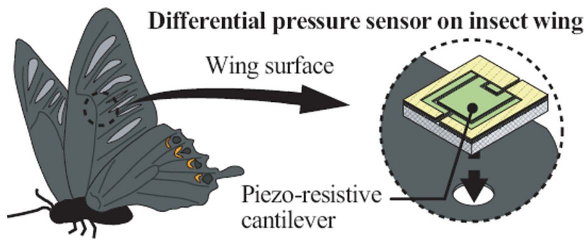

Figure 10. Piezoelectric differential air-pressure sensor for an insect wing (Takahashi et al., 2010).

using piezoelectric sensors to measure structural strains under high-frequency loading was developed (Kosmatka and Oliver, 2006). Piezoelectric sensors have been used to monitor the load and deformation bifurcations of a multi-stable structure to control its motion (Zareie et al., 2011). This type of sensor can also be used to measure the velocity of a morphing structure (Ray and Batten, 2012). Figure 10 shows a device with a piezo-resistive cantilever that was able to detect the differential pressure over the wing surface of an insect (Takahashi et al., 2009, 2010).

Electro-active polymers

Similar to piezoelectric materials, EAPs can also generate electrical signals and can be used for flexible structures and large strain conditions. Figure 11 shows a flapping wing MAV with EAP sensors on its wings (Hsu et al., 2006; Yang et al., 2007). The lift in flight was obtained from the EAP sensors. These results were verified in a wind tunnel test and flight tests. EAP sensors can also be used for monitoring vibrating structures (Sahu et al., 2013).

Self-sensing is another main feature of smart materials. Smart materials have sensing capabilities with some environmental parameters such as stress, strain, temperature and the location of structure damage and feedback some measurable signals. However, these sensors based on smart material also have some deficiencies stated as follows. Wire signal transmission system is so complex and ponderous, which causes much inconvenience in applying. In order to solve this problem, a type of wireless transmission system is already being developed. Moreover, since there is a limit on the number of channels in signal demodulation system, it is desired to realize a demodulation system capable of multi-signal processing. In addition, some sensors are prone to snapping such as optical fiber sensor and piezoelectric ceramics sensor or tearing such as EAP.

Structures

Auxetic honeycomb structures

Unlike traditional honeycomb structures, an auxetic structure is one that becomes wider when it is stretched (Evans and Alderson, 2000), and therefore, it has a negative Poisson's ratio (Prawoto, 2012). Auxetic honeycomb structures have other advantages for morphing structures (Luo and Tong, 2013a, 2013b). Variable-camber wings have been designed using several types of auxetic structures, including reentrant hexagonal honeycombs (Dong and Sun, 2011; Heo et al., 2013; Vigliotti and Pasini, 2015), chiral honeycombs (Airoldi et al., 2012; Bornengo et al., 2005; Martin et al., 2008; Spadoni and Ruzzene, 2007), and cross-shaped honeycombs (Zhang et al., 2012, 2014). Zero-Poisson's-ratio honeycombs have been used in variable-span morphing wings (Ajaj et al., 2012; Bubert et al., 2010; Chen et al., 2015; Gong et al., 2015; Liu et al., 2013; Olympio and Gandhi, 2010; Vocke et al., 2012, 2015). Figure 12 shows a variable-span morphing wing with a 100% extension (Vocke et al., 2011). Similar approaches have been used to create variable-chord wing structures (Barbarino et al., 2011b; Chen et al., 2013d; Dale et al., 2014). Adaptive wings have been constructed by adding pressured air in the sealed honeycombs to obtain the optimal configuration for a given flight condition (Barrett and Barrett, 2014; Vos and Barrett, 2010a,

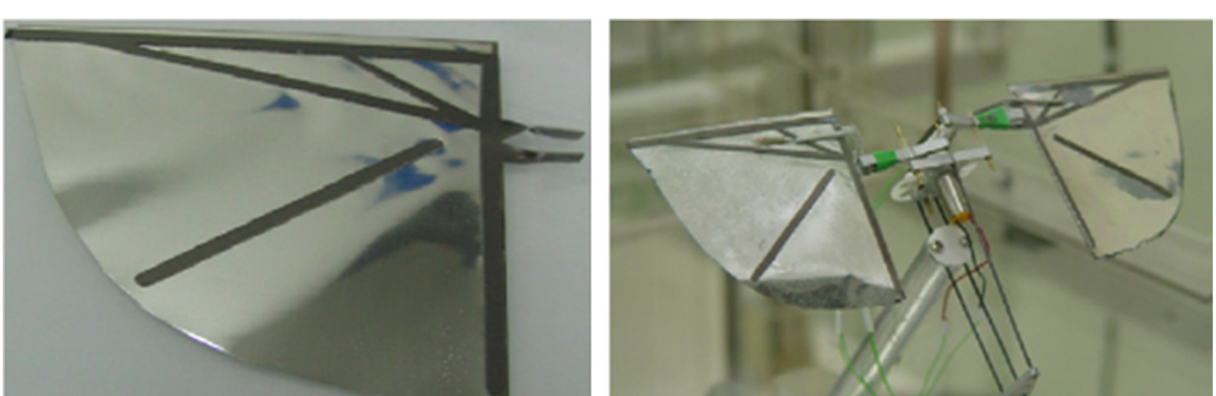

Figure 11. EAP sensors on a flapping wing MAV (Yang et al., 2007).

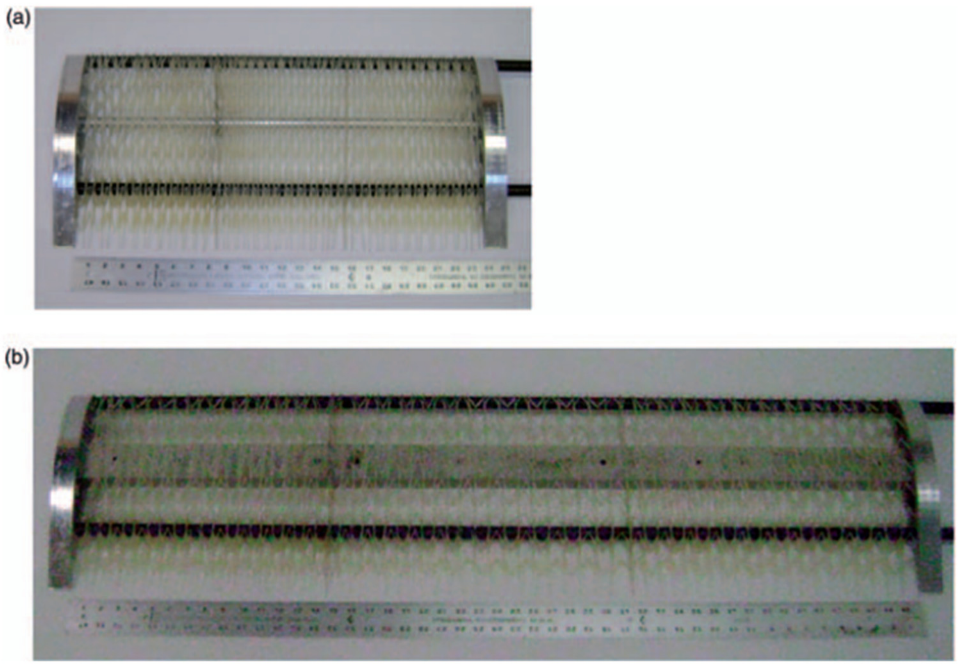

Figure 12. Variable-span morphing wings based on zero-poisson's-ratio honeycombs: (a) contracted state and (b) extended state (Vocke et al., 2011).

2010b, 2011). A pressurized honeycomb has also been used as the actuator in a morphing wingtip structure (Sun et al., 2014a). Other honeycomb designs have been used in wing boxes (Saito et al., 2011) and engine fan blades (Lira et al., 2011).

Variable-stiffness tube structures

There is a contradiction in morphing structures, which means the structure must be both strong and deformable. A structure with variable stiffness is required. Shape memory polymers are variable-stiffness materials, as discussed in section "Shape memory polymers." This section discusses the use of variable-stiffness tubes and a flexible matrix to create a structure. There are three types of variable-stiffness tubes. The first type is a pneumatic tube, which is also called a pneumatic muscle fiber. Pneumatic muscle fibers have been used as actuators (Vanderhoff and Kim, 2009) that shorten under air-pressure loads. In this process, the stiffness of the tube changes dramatically. Pneumatic muscle fibers can be added to a flexible matrix to form a morphing skin, where the transverse stiffness ratio can be as high as 120 (Chen et al., 2011). This morphing skin was also used in a variable-camber wing structure as both actuator and skin (Feng et al., 2015).

The second type of variable-stiffness tube is the SMP composite tube, a carbon fiber filament-wound tube cured with SMP resin. In one set of studies, the modulus ratio of a morphing skin created using SMP composite tubes was 59.6 according to tensile tests (Chen et al., 2012b, 2013a). Photographs of the out-of-plane deformation under uniform loading as the tube was being heated are shown in Figure 13.

The third type of variable-stiffness tube is called a fluidic flexible matrix composite (F^2MC) tube. The stiffness of the tube is controlled by the pressure of a fluid inside the tube. Pressurizing the fluid causes a sharp increase in the stiffness because of the special anisotropic tube structure and the incompressibility of the fluid. The modulus ratio of a skin made with F^2MC tubes can reach 55.5 (Shan et al., 2009), and the theoretical maximum modulus ratio can be 120 (Chen et al., 2012a). To obtain a larger modulus ratio, SMPs can be used for the matrix to form F^2MC-reinforced SMP composites (Philen et al., 2009). The modulus ratio for these types can reach 140, which can allow the material to withstand conditions that could damage an F^2MC. This type of tube has been used as an actuator to drive a morphing wing structure (Doepke et al., 2014).

Multi-stable structures

A multi-stable structure has two or more stable states, and the structure can transition rapidly from one to the other when stimulated. Multi-stable structures have been used for morphing wing UAVs (Daynes and Weaver, 2013b; Mattioni et al., 2008). Multi-stable structures have been used to construct variable-sweep wings. In tests, the wings successfully transitioned from straight to fully swept (Mattioni et al., 2006). A

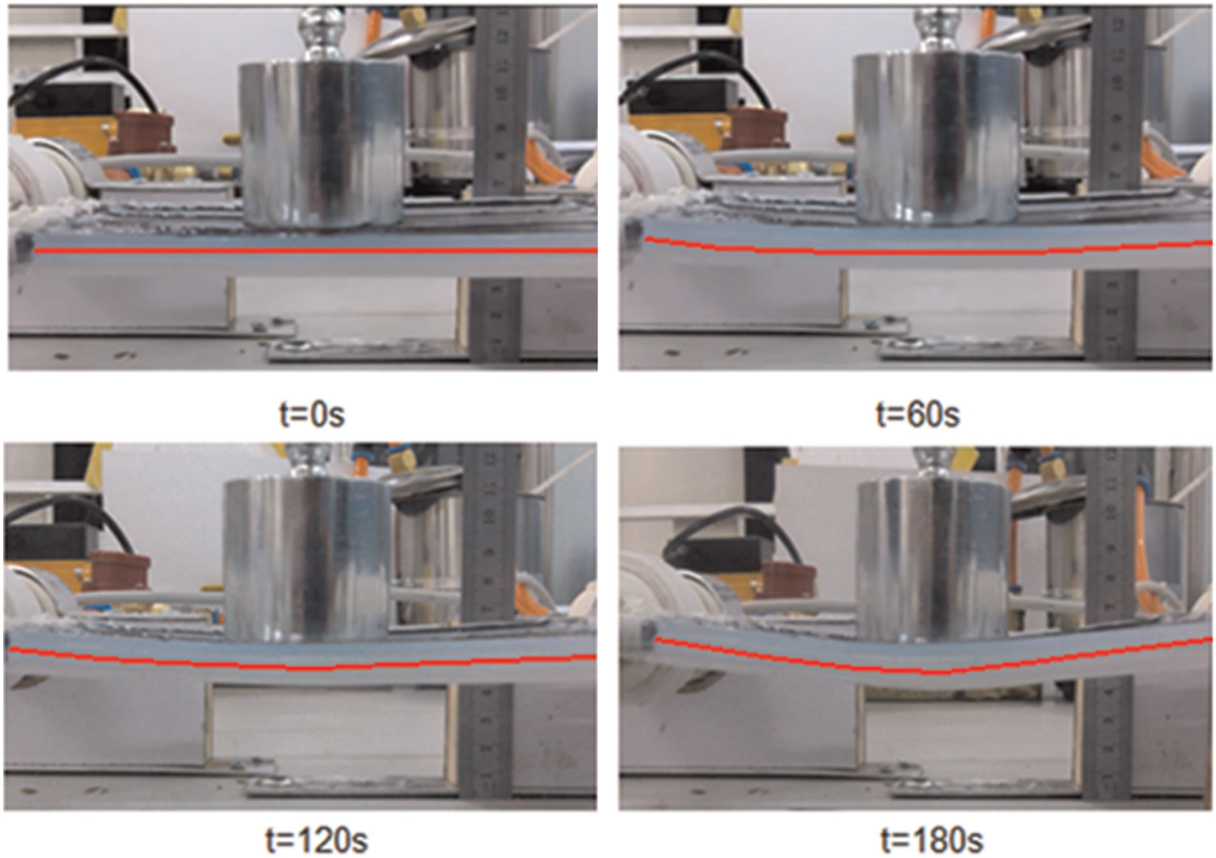

Figure 13. Deformation of a morphing skin with SMP composite tubes (Chen et al., 2013a).

twisting structure has been manufactured based on bi-stable structures actuated by MFCs to control a UAV (Schultz, 2005). Morphing wing trailing edges have been designed to control four states by changing the upper surface and the lower surface, both of which are made of bi-stable structures (Mattioni et al., 2007). An adaptive morphing-airfoil wing has been designed with a bi-stable structure that switches between stiff and compliant modes (Arrieta et al., 2014). A morphing wingtip structure based on a bi-stable structure can provide the optimal wing configurations for takeoff and cruise (Friswell et al., 2006), which can be determined from wind tunnel tests (see Figure 14). A morphing air inlet using multi-stable structures that switches between the open and closed positions to either create a flush surface or form a submerged air duct with a divergent–convergent channel has been constructed (Daynes et al., 2011). An actuator is designed to operate at a first working temperature while in a preceding manufacturing process the first layer of material is structurally connected to a support beam at a second temperature wherein the second temperature is higher than the first temperature so as to cause that at the first temperature the support beam is in compression without causing flexure thereof (Barrett and Tiso, 2011). SMA-actuated post-buckled pre-compressed (PBP) plates are capable of tip deflection of up to 45°, and that the PBP mechanism improves tip rotation up to 40% compared to conventional antagonistically actuated SMA plates (Sinn and Barrett, 2010).

Corrugated structures

Corrugated structures can undergo a large expansion or contraction in one direction. These structures are additionally suited for folding or bending (Dayyani et al., 2015; Previtali et al., 2014a). Within a specified range of Reynolds numbers, eddies form over the corrugated surface, similar to streamlined airfoils (Xia et al., 2014). Morphing trailing-edge structures can be covered with corrugated skins (Shaw et al., 2015). There are two methods to make corrugated structures smooth. One method is to fill the structure with flexible rubber (Yokozeki et al., 2006, 2014), and the other method is to cover it with a segmented skin similar to fish scales (Thill et al., 2010). Figure 15 shows a morphing winglet with a corrugated structure in which a 0.52 rad change in dihedral angle and 0.055 rad change in twist angle were achieved (Ursache et al., 2008). Corrugated structures have been used in a flapping artificial insect wing whose aerodynamic behavior was analyzed (Meng et al., 2010).

Smart structures are distinct from the traditional bearing structures, since smart structures emphasize

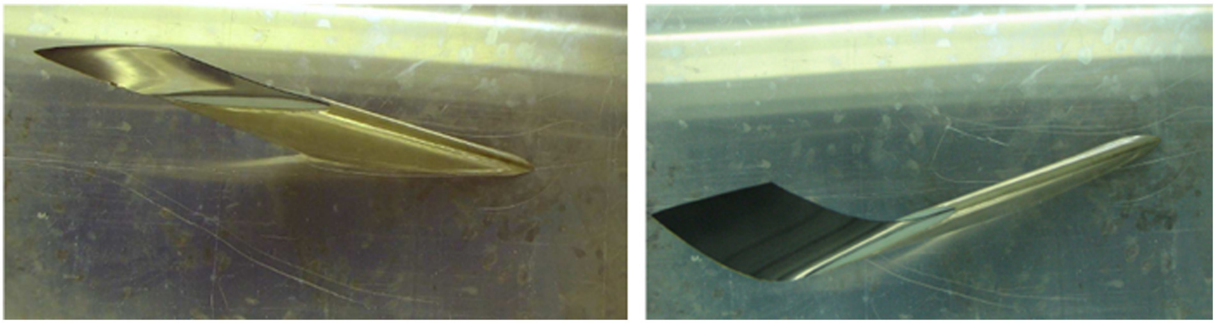

Figure 14. Wind-tunnel test rig for a winglet incorporating bi-stable structures (Mattioni et al., 2007).

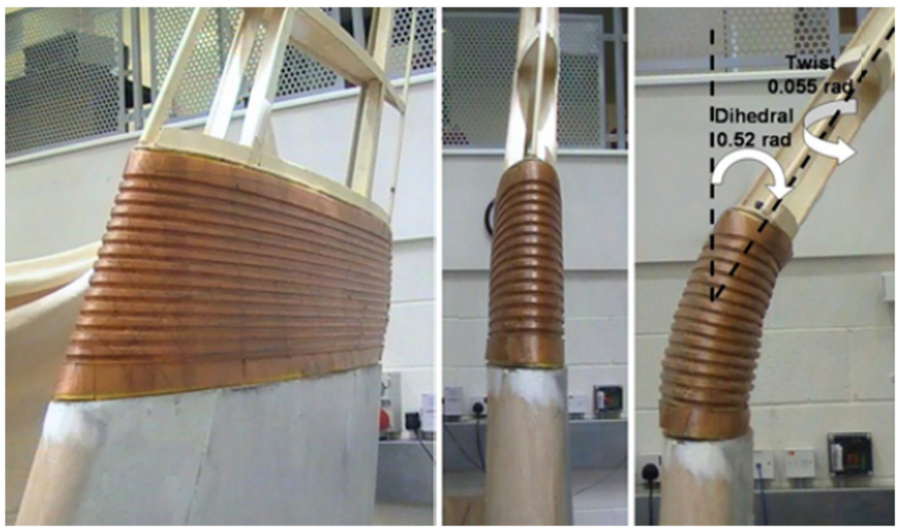

Figure 15. Demonstration of extension and canting of a morphing winglet with a corrugated structure (Ursache et al., 2008).

more the feature of deformability and designability. For different deformation structures of morphing aircraft, a structure capable of carrying and deforming is the base of actuator and sensors. These current designs of lightweight deformation structure have good performance on the bearing and deformation capacity, but there are still some problems about the relationship between deformation structures and smooth configuration to be solved. There are two potential solutions as follows. First one, smooth configurations could be realized by finding a valid method to connect flexible skin to deformation structures. Second, searching for theoretical support build unsmooth configurations which also have good performance on some special aerodynamic efficiency.

Controllers

Active vibration control

Vibration and noise significantly affect the comfort and the safety of an aircraft. Smart materials and structures have been used to reduce the vibration of rotor blades, for example, by twisting the blades or controlling a trailing-edge flap (Chen and Chopra, 1997; Giurgiutiu, 2000a). Aircraft engine rotor vibrations and bearing forces can be reduced using piezoelectric actuators (Leboi et al., 2010). Vibrations in the wings (Munteanu and Ursu, 2008) and the vertical stabilizer (Chen et al., 2013b; Gao et al., 2013) can be reduced dramatically using piezoelectric actuators as active dampers. An active buffet alleviation system has been tested on a 1/16th-scale model of a vertical stabilizer in a wind tunnel (Hanagud et al., 2002). Active vibration control has been used for buffet load alleviation on a full-scale F/A-18 vertical stabilizer (Chen et al., 2006); the test rig is shown in Figure 16.

To achieve a comfortable environment in an airplane, the interior broadband noise can be reduced using smart actuators (Dimino and Concilio, 2010; Guigou and Fuller, 1998; Konstanzer et al., 2006; Rose et al., 2011). Piezoelectric actuators were used to reduce engine noise and unsteady flow over an aft fuselage panel during takeoff on a Boeing B-1B high-performance combat aircraft (Larsona et al., 1998).

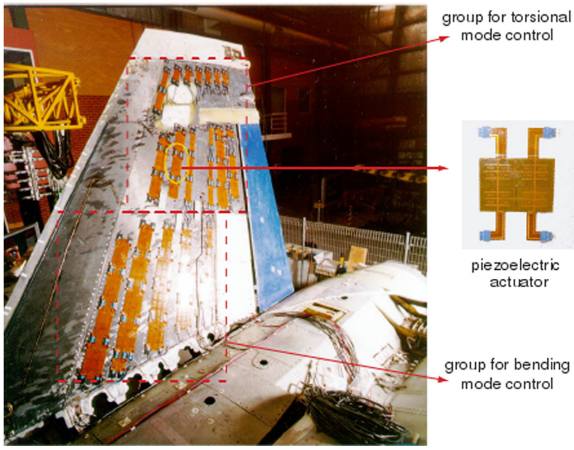

Figure 16. Active vibration control of an F/A-18 vertical stabilizer with piezoelectric actuators (Chen et al., 2006).

Airflow control

The aerodynamic behavior of a body can be improved through small changes in its surface. Piezoelectric ceramic actuators have been used with a compliant upper wing surface to create an active wall that can be made to oscillate to reduce skin friction (Pätzold et al., 2013). Transonic drag has been reduced using a morphing wing airfoil driven by SMAs (Barbarino et al., 2009a). An active vibrating surface can reduce drag and increase lift, as was demonstrated on a 1/10-scale V-22 model in a wind tunnel (Calkins and Clingman, 2002). The use of a linear array of micro-flaps on a delta wing to generate rolling moments to control a tailless aircraft has been demonstrated in a wind tunnel (Liu et al., 1995). A novel wing with smooth, hingeless morphing ailerons that increase the chordwise aerodynamic efficiency has been developed (Pankonien and Inman, 2013), as shown in Figure 17. The capability of this type of control surface to maintain stability and increase efficiency has been demonstrated in wind tunnel tests and in flight tests (Bilgen et al., 2013).

At this point, the smart materials are not applied as real controllers but actuating units. Controllers based on smart materials put more emphasis on the active control of structures such as active vibration control and airflow control. Controllers, sensors and actuators, and smart structures combine electronic technology to form a smart system capable of sensing, processing, and actuating, which will be the developing trend of smart materials and structures.

Conclusion

In this article, applications of smart materials and structures in morphing aircraft were reviewed. These materials are already being used in several micro air vehicles, unmanned aerial vehicles, and full-size aircraft, suggesting the great potential of smart materials and structures in morphing aircraft. However, smart materials and structures are not currently suitable for production aircraft. To realize the full potential of these devices, multi-scale design and multi-disciplinary research should be considered, and the following five challenges should be addressed:

1. *Material modification*. At the molecular scale, amputation, grafting, or recombination technology could be used to improve the performance of current smart materials.
2. *Functional additives*. Additives (e.g. carbon nanotubes, carbon black, graphite, ferrous powders, and nickel powders) could be incorporated into smart composites to make them multifunctional. For example, SMPs can be heated electrically by incorporating conductive additives (Leng et al., 2007, 2008, 2009; Lu et al., 2010).
3. *Structure optimization*. Optimized structures can be designed using topology optimization methods (Vasista and Tong, 2013). Moreover, novel structures may be discovered by applying new concepts (Chen et al., 2013c; Fischer et al., 2011; Wu et al., 2014).
4. *Hybrid applications*. Novel structures can be constructed using various smart materials; for example, honeycombs constructed using SMAs (Hassan et al., 2008; Okabe and Sugiyama, 2009) or SMPs (Rossiter et al., 2014), bi-stable-structure actuators constructed from MFCs

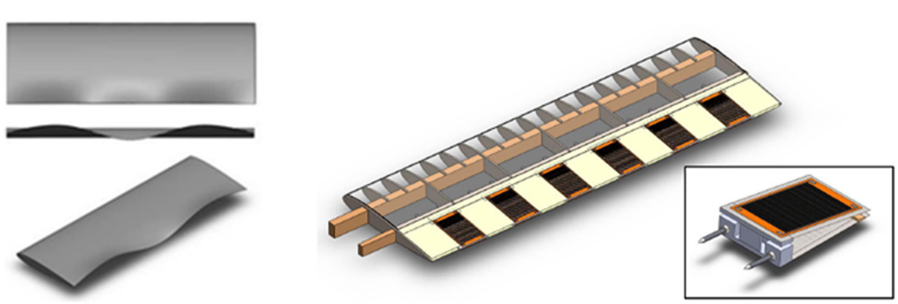

Figure 17. Discrete aileron controlled by MFC (Pankonien and Inman, 2013).

(Giddings et al., 2011; Molinari et al., 2014; Schultz and Hyer, 2004), and hybrid linear step actuators driven by magnetostrictive or piezoelectric materials (Ueno et al., 2007).

5. *Novel smart materials*. Many types of novel smart materials are required, and efforts should be made to create and investigate them.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work is supported by the National Natural Science Foundation of China (Grant Nos 11225211 and 11272106).

References

Abdullah EJ, Bil C and Watkins S (2011) Performance of adaptive airfoil control system using shape memory alloy actuators for UAV. In: *Proceedings of the 11th AIAA aviation technology, integration, and operations (ATIO) conference*, Virginia Beach, VA, 20–22 September, AIAA 2011-6849.

Airoldi A, Crespi M, Quaranta G, et al. (2012) Design of a morphing airfoil with composite chiral structure. *Journal of Aircraft* 49(4): 1008–1019.

Ajaj RM, Friswell MI, Flores EIS, et al. (2012) Span morphing: a conceptual design study. In: *Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Honolulu, HI, 23–26 April, AIAA 2012-1510.

Ameduri S, Brindisi A, Tiseo B, et al. (2011) Optimization and integration of shape memory alloy (SMA)-based elastic actuators within a morphing flap architecture. *Journal of Intelligent Material Systems and Structures*. Epub ahead of print 17 November. DOI: 10.1177/1045389X11428672.

Arrieta AF, Kuder IK, Rist M, et al. (2014) Passive load alleviation aerofoil concept with variable stiffness multi-stable composites. *Composite Structures* 116: 235–242.

Baier H and Datashvili L (2011) Active and morphing aerospace structures—a synthesis between advanced materials, structures and mechanisms. *International Journal of Aeronautical and Space Sciences* 12(3): 225–240.

Barbarino S, Ameduri S, Lecce L, et al. (2009a) Wing shape control through an SMA-based device. *Journal of Intelligent Material Systems and Structures* 20: 283–296.

Barbarino S, Bilgen O, Ajaj RM, et al. (2011a) A review of morphing aircraft. *Journal of Intelligent Material Systems and Structures* 22: 823–877.

Barbarino S, Flores ES, Ajaj RM, et al. (2014) A review on shape memory alloys with applications to morphing aircraft. *Smart Materials and Structures* 23(6): 063001.

Barbarino S, Gandhi F and Webster SD (2011b) Design of extendable chord sections for morphing helicopter rotor blades. *Journal of Intelligent Material Systems and Structures* 22: 891–905.

Barbarino S, Pecora R, Lecce L, et al. (2009b) A novel SMA-based concept for airfoil structural morphing. *Journal of Materials Engineering and Performance* 18(5–6): 696–705.

Barbarino S, Pecora R, Lecce L, et al. (2011c) Airfoil structural morphing based on S.M.A. actuator series: numerical and experimental studies. *Journal of Intelligent Material Systems and Structures* 22: 987–1003.

Bar-Cohen Y (2000) Electroactive polymers as artificial muscles—capabilities, potentials and challenges (Section 11, in Chapter 8, "Motion" paper). In: Osada Y (ed.) *Handbook on Biomimetics*. Tokyo: NTS, pp. 1–13.

Bar-Cohen Y (2002) Electro-active polymers: current capabilities and challenges. In: *Proceedings of SPIE smart structures and materials 2002: electroactive polymer actuators and devices (EAPAD)*, San Diego, CA, 17 March, vol. 4695.

Barrett RM (1996) Active aeroelastic tailoring of an adaptive Flexspar stabilator. *Smart Materials and Structures* 5: 723–730.

Barrett RM and Barrett C (2014) Biomimetic FAA-certifiable, artificial muscle structures for commercial aircraft wings. *Smart Materials and Structures* 23: 074011.

Barrett RM and Stutts J (1997) Design and testing of a 1/12th-scale solid state adaptive rotor. *Smart Materials and Structures* 6: 491–497.

Barrett RM and Stutts J (1998) Development of a piezoceramic flight control surface actuator for highly compressed munitions. In: *Proceedings of 39th structures, structural dynamics and materials conference*, Long Beach, CA, 20–23 April, AIAA 98-2034, pp. 2807–2813. Reston, VA: AIAA.

Barrett RM and Tiso P (2011) *Actuator*. Patent no. 7,898,153, USA, 1 March.

Barrett RM, Frye P and Schliesman M (1998) Design, construction and characterization of a flightworthy piezoelectric solid state adaptive rotor. *Smart Materials and Structures* 7: 422–431.

Bent AA and Pizzochero AE (2000) Recent advances in active fiber composites for structural control. In: *Proceedings of SPIE smart structures and materials 2000: industrial and commercial applications of smart structures technologies*, Newport Beach, CA, 6 March, vol. 3991, pp. 244–254. Bellingham, WA: SPIE.

Bhavsar R, Vaidya NY, Ganguly P, et al. (2008) Intelligence in novel materials. *Oilfield Review* 20(1): 32–41.

Bilgen O and Friswell MI (2014) Piezoceramic composite actuators for a solid-state variable-camber wing. *Journal of Intelligent Material Systems and Structures* 25(7): 806–817.

Bilgen O, Butt LM, Day SR, et al. (2013) A novel unmanned aircraft with solid-state control surfaces: analysis and flight demonstration. *Journal of Intelligent Material Systems and Structures* 24: 147–167.

Bilgen O, Kochersberger K, Diggs EC, et al. (2007) Morphing wing micro-air-vehicles via macro-fiber-composite actuators. In: *Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Honolulu, HI, 23–26 April, AIAA 2007-1785.

Bogue R (2012) Smart materials: a review of recent developments. *Assembly Automation* 32: 3–7.

Bornengo D, Scarpa F and Remillat C (2005) Evaluation of hexagonal chiral structure for morphing airfoil concept. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 219: 185–192.

Brailovski V, Terriault P, Georges T, et al. (2010) SMA actuators for morphing wings. *Physics Procedia* 10: 197–203.

Bridger K, Sewell JM, Cooke AV, et al. (2004) High-pressure magnetostrictive pump development: a comparison of prototype and modeled performance. In: *Proceedings of SPIE smart structures and materials 2004: industrial and commercial applications of smart structures technologies*, San Diego, CA, 14 March, vol. 5388, pp. 247–257. Bellingham, WA: SPIE.

Bubert EA, Woods BKS, Lee K, et al. (2010) Design and fabrication of a passive 1D morphing aircraft skin. *Journal of Intelligent Material Systems and Structures* 21: 1699–1716.

Bushnell GS, Arbogast D and Ruggeri R (2008) Shape control of a morphing structure (rotor blade) using a shape memory alloy actuator system. In: Proceedings of SPIE active and passive smart structures and integrated systems 2008, San Diego, CA, 9 March, vol. 6928, p. 69282A. Bellingham, WA: SPIE.

Bye DR and McClure PD (2007) Design of a morphing vehicle. In: *Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Honolulu, HI, 23–26 April, AIAA 2007-1728.

Calkins FT and Clingman DJ (2002) Vibrating surface actuators for active flow control. In: *Proceedings of SPIE smart structures and materials 2002: industrial and commercial applications of smart structures technologies*, San Diego, CA, 17 March, vol. 4698, pp. 85–96. Bellingham, WA: SPIE.

Calkins FT and Mabe JH (2010) Shape memory alloy based morphing aerostructures. *Journal of Mechanical Design* 132: 111012.

Calkins FT, Mabe JH and Butler GW (2006) Boeing's variable geometry chevron: morphing aerospace structures for jet noise reduction. In: *Proceedings of SPIE smart structures and materials 2006: industrial and commercial applications of smart structures technologies*, San Diego, CA, 26 February, vol. 6171, p. 61710O. Bellingham, WA: SPIE.

Cantrell JT and Ifju PG (2015) Experimental characterization of unimorph shape memory polymer actuators incorporating transverse curvature in the substrate. *Experimental Mechanics* 55(8): 1395–1409.

Chapman EG, Herdic SL, Keller CA, et al. (2005) Development of miniaturized piezo-hydraulic pumps. In: *Proceedings of SPIE smart structures and materials 2005: industrial and commercial applications of smart structures technologies*, San Diego, CA, 6 March, vol. 5762, pp. 299–310. Bellingham, WA: SPIE.

Chaudhuri A and Wereley NM (2010) Experimental validation of a hybrid electrostrictive hydraulic actuator analysis. *Journal of Vibration and Acoustics* 132: 021006.

Chaudhuri A, Yoo JH and Wereley NM (2009) Design, test and model of a hybrid magnetostrictive hydraulic actuator. *Smart Materials and Structures* 18: 085019.

Chen J, Shen X and Li J (2015) Zero Poisson's ratio flexible skin for potential two-dimensional wing morphing. *Aerospace Science and Technology* 45: 228–241.

Chen PC and Chopra I (1997) Wind tunnel test of a smart rotor with individual blade twist control. In: *Proceedings of SPIE's North American conference on smart structures and materials*, San Diego, CA, 3–6 March, vol. 3041, pp. 217–230. Bellingham, WA: SPIE.

Chen SB, Chen YJ, Zhang ZC, et al. (2013a) Experiment and analysis of morphing skin embedded with shape memory polymer composite tube. *Journal of Intelligent Material Systems and Structures*. Epub ahead of print 31 December. DOI: 10.1177/1045389X13517307.

Chen Y, Ulker FD, Wickramasinghe V, et al. (2013b) Development of robust control law for active buffeting load alleviation of smart fin structures. *Journal of Intelligent Material Systems and Structures*. Epub ahead of print 11 June. DOI: 10.1177/1045389X13491639.

Chen Y, Viresh W and Zimcik D (2006) Development and verification of real-time controllers for F/A-18 vertical fin buffet load alleviation. In: *Proceedings of SPIE smart structures and materials 2006: smart structures and integrated systems*, San Diego, CA, 26 February, vol. 6173, p. 617310. Bellingham, WA: SPIE.

Chen YJ, Scarpa F, Farrow IR, et al. (2013c) Composite flexible skin with large negative Poisson's ratio range: numerical and experimental analysis. *Smart Materials and Structures* 22: 045005.

Chen YJ, Scarpa F, Remillat C, et al. (2013d) Curved Kirigami SILICOMB cellular structures with zero Poisson's ratio for large deformations and morphing. *Journal of Intelligent Material Systems and Structures* 25: 731–743.

Chen YJ, Sun J, Liu YJ, et al. (2012a) Experiment and analysis of fluidic flexible matrix composite (F^2MC) tube. *Journal of Intelligent Material Systems and Structures* 23(3): 279–290.

Chen YJ, Sun J, Liu YJ, et al. (2012b) Variable stiffness property study on shape memory polymer composite tube. *Smart Materials and Structures* 21: 094021.

Chen YJ, Yin WL, Liu YJ, et al. (2011) Structural design and analysis of morphing skin embedded with pneumatic muscle fibers. *Smart Materials and Structures* 20: 085033.

Chung DDL (2004) Self-heating structural materials. *Smart Materials and Structures* 13: 562–565.

Ciminello M, Concilio A, Flauto D, et al. (2013) FBG sensor system for trailing edge chord-wise hinge rotation measurements. In: *Proceedings of SPIE sensors and smart structures technologies for civil, mechanical, and aerospace systems 2013*, San Diego, CA, 10 March, vol. 8692, p. 869221. Bellingham, WA: SPIE.

Cistone J (2004) Next century aerospace traffic management: the sky is no longer the limit. *Journal of Aircraft* 41(1): 36–42.

Claeyssen F, Lhermet N and Maillard T (2002) Magnetostrictive actuators compared to piezoelectric actuators. In: *Proceedings of the SPIE European workshop on smart structures in engineering and technology*, Giens, 21 May, vol. 4763, pp. 194–200. Bellingham, WA: SPIE.

Colozza A (2007) Fly like a bird—flapping wings could revolutionize aircraft design. *IEEE Spectrum*, 1 May, pp. 39–43.

Costa J, Black RJ, Moslehi B, et al. (2014) Fiber-optically sensorized composite wing. In: *Proceedings of SPIE smart sensor phenomena, technology, networks, and systems integration 2014*, San Diego, CA, 9 March, vol. 9062, p. 906213. Bellingham, WA: SPIE.

Craig D (1996) Near piezoelectric actuator technology. In: *Proceedings of SPIE smart structures and materials 1996: smart structures and integrated systems*, San Diego, CA, 25 February, vol. 2717, pp. 246–258. Bellingham, WA: SPIE.

Cusano A, Capoluongo P, Campopiano S, et al. (2006) Experimental modal analysis of an aircraft model wing by embedded fiber Bragg grating sensors. *IEEE Sensors Journal* 6(1): 67–77.

Dale AS, Cooper JE and Mosquera A (2014) Topology optimization and experimental validation of 0-υ honeycomb for adaptive morphing wing. In: *Proceedings of the AIAA SciTech, 22nd AIAA/ASME/AHS adaptive structures conference*, National Harbor, MD, 13–17 January, AIAA 2014-0763.

Davis C, Tejedor S, Grabovac I, et al. (2012) High-strain fiber Bragg gratings for structural fatigue testing of military aircraft. *Photonic Sensors* 2(3): 215–224.

Daynes S and Weaver PM (2013a) Review of shape-morphing automobile structures: concepts and outlook. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. Epub ahead of print 1 August. DOI: 10.1177/0954407013496557.

Daynes S and Weaver PM (2013b) Stiffness tailoring using prestress in adaptive composite structures. *Composite Structures* 106: 282–287.

Daynes S, Weaver PM and Trevarthen JA (2011) A morphing composite air inlet with multiple stable shapes. *Journal of Intelligent Material Systems and Structures* 22: 961–973.

Dayyani I, Shaw AD, Flores ES, et al. (2015) The mechanics of composite corrugated structures: a review with applications in morphing aircraft. *Composite Structures* 133: 358–380.

Dimino I and Concilio A (2010) A feedforward control system for the active noise control of a triple-pane aircraft-type window. In: *Proceedings of the 17th international congress on sound and vibration*, Cairo, Egypt, 18–22 July, pp. 1–8.

Doepke EB, Philen MK and West RL (2014) Design and optimization of a morphing aileron control surface using FMC actuators. In: *Proceedings of SPIE sensors and smart structures technologies for civil, mechanical, and aerospace systems 2014*, San Diego, CA, 9 March, vol. 9061, p. 90613H. Bellingham, WA: SPIE.

Donadon MV and Iannucci L (2014) A numerical study on smart material selection for flapped and twisted morphing wing configurations. *Journal of Aerospace Technology and Management* 6(3): 281–290.

Dong WJ and Sun Q (2011) Airfoil design and numerical analysis for morphing wing structure. *Advanced Materials Research* 228–229: 169–173.

Ehlers SM and Weisshaar TA (1990) Static aeroelastic behavior of an adaptive laminated piezoelectric composite wing. *AIAA Journal* 28: 1611–1623.

Evans KE and Alderson KL (2000) Auxetic materials: the positive side of being negative. *Engineering Science and Education Journal* 9(4): 148–154.

Feng N, Liu LW, Liu YJ, et al. (2015) A bio-inspired, active morphing skin for camber morphing structures. *Smart Materials and Structures* 24: 035023.

Fischer C, Terriault P and Brailovskic V (2011) Debonding characterization of SMA/polymer morphing structures. *Advanced Materials Research* 409: 621–626.

Friswell MI, Baker D, Herencia JE, et al. (2006) Compliant structures for morphing aircraft. In: *Proceedings of ICAST2006: 17th international conference on adaptive structures and technologies*, Taipei, Taiwan, 16–19 October, pp. 17–24.

Frommer JB and Crossley WA (2005) Enabling continuous optimization for sizing morphing aircraft concepts. In: *Proceedings of the 43rd AIAA aerospace sciences meeting and exhibit*, Reno, NV, 10–13 January, AIAA 2005-2816.

Galantai VP, Sofla AYN, Meguid SA, et al. (2012) Bio-inspired wing morphing for unmanned aerial vehicles using intelligent materials. *International Journal of Mechanics and Materials in Design* 8: 71–79.

Gao L, Lu QQ, Fei F, et al. (2013) Active vibration control based on piezoelectric smart composite. *Smart Materials and Structures* 22: 125032.

Georges T, Brailovski V and Terriault P (2012) Design of active bias SMA actuators for morphing wing applications. *Advanced Materials Research* 409: 627–632.

Giddings PF, Kim HA, Salo AIT, et al. (2011) Modelling of piezoelectrically actuated bistable composites. *Materials Letters* 65(9): 1261–1263.

Giurgiutiu V (2000a) Active-Materials induced-strain actuation for aeroelastic vibration control. *Shock and Vibration Digest* 32(5): 355–368.

Giurgiutiu V (2000b) Recent advances in smart-material rotor control actuation. In: *Proceedings of the 41st AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference, and adaptive structures forum*, Atlanta, GA, 3–6 April, AIAA 2000-1709.

Giurgiutiu V (2011) Review of smart-materials actuation solutions for aeroelastic and vibration control. *Journal of Intelligent Material Systems and Structures* 11: 525–544.

Giurgiutiu V, Chaudhry Z and Rogers CA (1994) Active control of helicopter rotor blades with induced strain actuators. In: *Proceedings of 35th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Hilton Head, SC, 18–20 April, AIAA-94-1765-CP.

Giurgiutiu V, Chaudhry Z and Rogers CA (1995) Engineering feasibility of induced-strain actuators for rotor blade active vibration control. *Journal of Intelligent Material Systems and Structures* 6: 583–597.

Gomez JC and Garcia E (2011) Morphing unmanned aerial vehicles. *Smart Materials and Structures* 20: 103001.

Gong X, Huang J, Scarpa F, et al. (2015) Zero Poisson's ratio cellular structure for two-dimensional morphing applications. *Composite Structures* 134: 384–392.

Grohmann B, Maucher C and Jänker P (2006) Actuation concepts for morphing helicopter rotor blades. In: *Proceedings of the 25th international congress of the aeronautical sciences (ICAS 2006)*, Hamburg, Germany, 3–8 September, pp. 1–10.

Guigou C and Fuller CR (1998) Control of aircraft interior broadband noise with foam-PVDF smart skin. *Journal of Sound and Vibration* 220(3): 541–557.

Hanagud S, De Noyer B, Luo H, et al. (2002) Tail buffet alleviation of high-performance twin-tail aircraft using piezostack actuators. *AIAA Journal* 40(4): 619–627.

Hao T (2001) Electrorheological fluids. *Advanced Materials* 13(24): 1847–1857.

Hartl DJ and Lagoudas DC (2007) Aerospace applications of shape memory alloys. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 221: 535–551.

Hartl DJ, Lagoudas DC, Calkins FT, et al. (2010a) Use of a Ni60Ti shape memory alloy for active jet engine chevron application, I: thermomechanical characterization. *Smart Materials and Structures* 19: 015020.

Hartl DJ, Mooney JT, Lagoudas DC, et al. (2010b) Use of a Ni60Ti shape memory alloy for active jet engine chevron application, II: experimentally validated numerical analysis. *Smart Materials and Structures* 19: 015021.

Hassan MR, Scarpa F, Ruzzene M, et al. (2008) Smart shape memory alloy chiral honeycomb. *Materials Science and Engineering: A* 481–482: 654–657.

Heo H, Ju J and Kim DM (2013) Compliant cellular structures: application to a passive morphing airfoil. *Composite Structures* 106: 560–569.

Heryawan Y, Park HC, Goo NS, et al. (2005) Design and demonstration of a small expandable morphing wing. In: *Proceedings of SPIE smart structures and materials 2005: smart structures and integrated systems*, San Diego, CA, 6 March, vol. 5764, pp. 224–231. Bellingham, WA: SPIE.

Heryawan Y, Park HC, Goo NS, et al. (2006) Structural design, manufacturing, and wind tunnel test of a small expandable wing. *Key Engineering Materials* 306–308: 1157–1162.

Hsu CK, Ho JY, Feng GH, et al. (2006) A flapping MAV (Micro Aerial Vehicle) with PVDF-parylene composite skin. In: *Proceedings of Asia-Pacific conference of transducers and micro-nano technology—APCOT 2006*, Singapore, 25–28 June.

Jacob JD and Smith SW (2009) Design limitations of deployable wings for small low altitude UAVs. In: *Proceedings of the 47th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition*, Orlando, FL, 5–8 January, AIAA 2009-1291.

Jaenker P, Kloeppel V, Konstanzer P, et al. (2008) Piezo active vibration and noise control in helicopters. In: *Proceedings of the 26th international congress of the aeronautical sciences*, Anchorage, Alaska, 14–19 September, pp. 1–10.

Jha AK and Kudva JN (2004) Morphing aircraft concepts, classifications, and challenges. In: *Proceedings of SPIE smart structures and materials 2004: industrial and commercial applications of smart structures technologies*, San Diego, CA, 14 March, vol. 5388, pp. 213–224. Bellingham, WA: SPIE.

Joshi SP, Tidwell Z, Crossley WA, et al. (2004) Comparison of morphing wing strategies based upon aircraft performance impacts. In: *Proceedings of the 45th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Palm Springs, CA, 19–22 April, AIAA 2004-1722.

Kang GY, Han GY, Kang JY, et al. (2006) Label-free protein assay with site-directly immobilized antibody using self-actuating PZT cantilever. *Sensors and Actuators B: Chemical* 117: 332–338.

Kang WR, Kim EH, Jeong MS, et al. (2012) Morphing wing mechanism using an SMA wire actuator. *International Journal of Aeronautical and Space Sciences* 13(1): 58–63.

Karagiannis D, Solomou A, Machairas T, et al. (2014) Airfoil morphing based on SMA actuation technology. *Aircraft Engineering and Aerospace Technology: An International Journal* 86(4): 295–306.

Kciuk M and Turczyn R (2006) Properties and application of magnetorheological fluids. *Journal of Achievements in Materials and Manufacturing Engineering* 18(1–2): 127–130.

Keihl MM, Bortolin RS, Sanders B, et al. (2005) Mechanical properties of shape memory polymers for morphing aircraft applications. In: *Proceedings of SPIE smart structures and materials 2005: industrial and commercial applications of smart structures technologies*, San Diego, CA, 6 March, vol. 5762, pp. 143–151. Bellingham, WA: SPIE.

Kim DK, Kim HI, Han JH, et al. (2008) Experimental investigation on the aerodynamic characteristics of a bio-mimetic flapping wing with macro-fiber composites. *Journal of Intelligent Material Systems and Structures* 19: 423–431.

Kim GW and Wang KW (2007) Piezoelectric-hydraulic pump based band brake actuation system for automotive transmission control. In: *Proceedings of SPIE active and passive smart structures and integrated systems 2007*, San Diego, CA, 18 March, vol. 6525, p. 65251E. Bellingham, WA: SPIE.

Kim HI, Kim DK and Han JH (2007) Study of flapping actuator modules using IPMC. In: *Proceedings of SPIE electroactive polymer actuators and devices (EAPAD) 2007*, San Diego, CA, 18 March, vol. 6524, p. 65241A. Bellingham, WA: SPIE.

Kim JH, Lee YG, Park Y, et al. (2013) Temperature-compensated strain measurement of full-scale small aircraft wing structure using low-cost FBG interrogator. In: *Proceedings of SPIE sensors and smart structures technologies for civil, mechanical, and aerospace systems 2013*, San Diego, CA, 10 March, vol. 8692, p. 86922P. Bellingham, WA: SPIE.

Kim WJ and Sadighi A (2010) A novel low-power linear magnetostrictive actuator with local three-phase excitation. *IEEE/ASME Transactions on Mechatronics* 15(2): 299–307.

Ko SH, Bae JS and Rho JH (2014) Development of a morphing flap using shape memory alloy actuators: the aerodynamic characteristics of a morphing flap. *Smart Materials and Structures* 23: 074015.

Konstanzer P, Enenkl B, Aubourg PA, et al. (2008) Recent advances in Eurocopter's passive and active vibration control. In: *Proceedings of the American helicopter society 64th annual forum*, Montréal, QC, Canada, 29 April–1 May.

Konstanzer P, Grünewald M, Jänker P, et al. (2006) Aircraft interior noise reduction through a piezo tunable vibration absorber system. In: *Proceedings of the 25th international congress of the aeronautical sciences (ICAS 2006)*, Hamburg, 3–8 September, pp. 1–6.

Koratkar NA and Chopra I (2000) Analysis and testing of mach-scaled rotor with trailing-edge flaps. *AIAA Journal* 38(7): 1113–1124.

Kosmatka JB and Oliver J (2006) Development of an in-flight structural health monitoring system for composite unmanned aircraft. In: *Proceedings of the 47th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Newport, RI, 1–4 May, AIAA 2006-1881.

Krstulovic-Opara N, Nau J, Wriggers P, et al. (2003) Self-actuating SMA-HPFRC fuses for auto-adaptive composite structures. *Computer-Aided Civil and Infrastructure Engineering* 18: 78–94.

Kruusamäe K, Brunetto P, Punning A, et al. (2011) Electromechanical model for a self-sensing ionic polymer–metal composite actuating device with patterned surface electrodes. *Smart Materials and Structures* 20: 124001.

Kuder IK, Arrieta AF, Raither WE, et al. (2013) Variable stiffness material and structural concepts for morphing applications. *Progress in Aerospace Sciences* 63: 33–55.

Kudva JN (2004) Overview of the DARPA smart wing project. *Journal of Intelligent Material Systems and Structures* 15: 261–267.

Larsona CR, Falangasa E, Dobbsa SK, et al. (1998) Piezoceramic active vibration suppression control system development for the B-lB aircraft. In: *Proceedings of SPIE smart structures and materials 1998: industrial and commercial applications of smart structures technologies*, San Diego, CA, 1 March, vol. 3326, pp. 294–305. Bellingham, WA: SPIE.

Leboi F, Rinderknecht S and Özet M (2010) Model-based control of an elastic aircraft engine rotor with piezo stack. In: *Proceedings of the 2010 IEEE 17th international conference on industrial engineering and engineering management (IE&EM)*, Xiamen, China, 29–31 October, pp. 537–541. New York: IEEE.

Lee JR, Ryu CY, Koo BY, et al. (2003) In-flight health monitoring of a subscale wing using a fiber Bragg grating sensor system. *Smart Materials and Structures* 12: 147–155.

Lee SG, Park HC, Pandita SD, et al. (2006) Performance improvement of IPMC (Ionic Polymer Metal Composites) for a flapping actuator. *International Journal of Control, Automation, and Systems* 4(6): 748–755.

Lee T and Chopra I (2001) Design of piezostack-driven trailing-edge flap actuator for helicopter rotors. *Smart Materials and Structures* 10: 15–24.

Leng JS, Lan X, Liu YJ, et al. (2008) Electrical conductivity of thermoresponsive shape-memory polymer with embedded micron sized Ni powder chains. *Applied Physics Letters* 92: 014104.

Leng JS, Lan X, Liu YJ, et al. (2011) Shape-memory polymers and their composites: stimulus methods and applications. *Progress in Materials Science* 56: 1077–1135.

Leng JS, Liu LW, Lv HB, et al. (2012) Applications for shape-memory polymer composites in aerospace. *JEC Composites Magazine* 72: 56–58.

Leng JS, Lu HB, Liu YJ, et al. (2007) Electroactivate shape-memory polymer filled with nanocarbon particles and short carbon fibers. *Applied Physics Letters* 91: 144105.

Leng JS, Lu HB, Liu YJ, et al. (2009) Shape-Memory polymers—a class of novel smart materials. *MRS Bulletin* 34: 848–855.

Leng JS, Yu K, Sun J, et al. (2015) Deployable morphing structure based on shape memory polymer. *Aircraft Engineering and Aerospace Technology: An International Journal* 87(3): 218–223.

Lentink D, Müller UK, Stamhuis EJ, et al. (2007) How swifts control their glide performance with morphing wings. *Nature* 46: 1082–1085.

Li P, Liu YJ and Leng JS (2013a) A new deformation monitoring method for a flexible variable camber wing based on fiber Bragg grating sensors. *Journal of Intelligent Material Systems and Structures*. Epub ahead of print 19 November. DOI: 10.1177/1045389X13510220.

Li P, Yan ZJ, Zhang L, et al. (2013b) Monitoring of deployment process of shape memory polymers for morphing structures with embedded fibre Bragg grating sensors. *Journal of Intelligent Material Systems and Structures* 25(10): 1224–1232.

Li P, Yan ZJ, Zhou KM, et al. (2013c) Monitoring static shape memory polymers using a fiber Bragg grating as a vector-bending sensor. *Optical Engineering* 52(1): 014401.

Lira C, Scarpa F and Rajasekaran R (2011) A gradient cellular core for aeroengine fan blades based on auxetic configurations. *Journal of Intelligent Material Systems and Structures* 22: 907–917.

Liu C, Tsao T, Tai YC, et al. (1995) Out-of-plane permalloy magnetic actuators for delta-wing control. In: *Proceedings of the IEEE micro electro mechanical systems, MEMS '95*, Amsterdam, 29 January–2 February, pp. 7–12. New York: IEEE.

Liu WD, Zhu H, Zhou SQ, et al. (2013) In-plane corrugated cosine honeycomb for 1D morphing skin and its application on variable camber wing. *Chinese Journal of Aeronautics* 26(4): 935–942.

Liu YJ, Du HY, Liu LW, et al. (2014) Shape memory polymers and their composites in aerospace applications: a review. *Smart Materials and Structures* 23: 023001.

Liu YJ, Lv HB, Lan X, et al. (2009) Review of electro-active shape-memory polymer composite. *Composites Science and Technology* 69: 2064–2068.

Lloyd PA (2007) Requirements for smart materials. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 221: 471–478.

Loverich JJ (2004) *Development of a new high specific power piezoelectric actuator*. Master's Thesis, The Pennsylvania State University, State College, PA.

Lu HB, Liu YJ, Gou JH, et al. (2010) Synergistic effect of carbon nanofiber and carbon nanopaper on shape memory polymer composite. *Applied Physics Letters* 96: 084102.

Luo QT and Tong LY (2013a) Adaptive pressure-controlled cellular structures for shape morphing, I: design and analysis. *Smart Materials and Structures* 22: 055014.

Luo QT and Tong LY (2013b) Adaptive pressure-controlled cellular structures for shape morphing, II: numerical and experimental validation. *Smart Materials and Structures* 22: 055015.

Mabe J (2008) Variable area jet nozzle for noise reduction using shape memory alloy actuators. In: *Proceedings of Acoustic'08 Paris*, Paris, 29 June–4 July, pp. 5487–5492.

Mabe J, Calkins FT and Ruggeri RT (2007) Full-scale flight tests of aircraft morphing structures using SMA actuators. In: *Proceedings of SPIE active and passive smart structures and integrated systems 2007*, San Diego, CA, 18 March, vol. 6525, p. 65251C. Bellingham, WA: SPIE.

McGowan AM, Horta LG, Harrison JS, et al. (1999) Research activities within NASA's morphing program. In: *The RTO AVT specialists' meeting on "structural aspects of flexible aircraft control,"* Ottawa, ON, Canada, 18–20 October.

McKnight G and Henry C (2005) Variable stiffness materials for reconfigurable surface applications. In: *Proceedings of*

SPIE smart structures and materials 2005: active materials: behavior and mechanics, San Diego, CA, 6 March, vol. 5761, pp. 119–126. Bellingham, WA: SPIE.

McKnight G and Henry C (2008) Large strain variable stiffness composites for shear deformations with applications to morphing aircraft skins. In: *Proceedings of SPIE behavior and mechanics of multifunctional and composite materials 2008*, San Diego, CA, 9 March, vol. 6929, p. 692919. Bellingham, WA: SPIE.

Manzo J, Garcia E, Wickenheiser A, et al. (2005) Design of a shape-memory alloy actuated macro-scale morphing aircraft mechanism. In: *Proceedings of the SPIE smart structures and materials 2005: smart structures and integrated systems*, San Diego, CA, 6 March, vol. 5764, pp. 232–240. Bellingham, WA: SPIE.

Martin CA, Kudva J, Austin F, et al. (1998) Smart materials and structures—smart wing, vols I, II, III and IV. *Report: AFRL-ML-WP-TR-1999-4162*, December. Hawthorne, CA: Northrop Grumman Corporation.

Martin J, Heyder-Bruckner JJ, Remillat C, et al. (2008) The hexachiral prismatic wingbox concept. *Physica Status Solidi B* 245(3): 570–577.

Mattioni F, Gatto A, Weaver PM, et al. (2006) The application of residual stress tailoring of snap-through composites for variable sweep wings. In: *Proceedings of the 47th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Newport, RI, 1–4 May, AIAA 2006-1972.

Mattioni F, Weaver PM, Friswell MI, et al. (2007) Modelling and applications of thermally induced multistable composites with piecewise variation of lay-up in the planform. In: *Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Honolulu, HI, 23–26 April, AIAA 2007-2262.

Mattioni F, Weaver PM, Potter KD, et al. (2008) The application of thermally induced multistable composites to morphing aircraft structures. In: *Proceedings of SPIE industrial and commercial applications of smart structures technologies 2008*, San Diego, CA, 9 March, vol. 6930, p. 693012. Bellingham, WA: SPIE.

MEMSnet (2014) Available at: https://www.memsnet.org/material/leadzirconatetitanatepzt/ (accessed 10 June 2014).

Meng XG, Xu L and Sun M (2010) Aerodynamic effects of corrugation in flapping insect wings in hovering flight. *Journal of Experimental Biology* 214: 432–444.

Michel S, Dürager C, Zobel M, et al. (2007) Electro active polymers as a novel actuator technology for lighter-than-air vehicles. In: *Proceedings of SPIE electroactive polymer actuators and devices (EAPAD) 2007*, San Diego, CA, 18 March, vol. 6524, p. 65241Q. Bellingham, WA: SPIE.

Mieloszyk M, Krawczuk M, Skarbek L, et al. (2011a) An application of neural network for structural health monitoring of an adaptive wing with an array of FBG sensors. *Journal of Physics: Conference Series* 305: 012066.

Mieloszyk M, Skarbek L, Krawczuk M, et al. (2011b) Application of fibre Bragg grating sensors for structural health monitoring of an adaptive wing. *Smart Materials and Structures* 20: 125014.

Molinari G, Arrieta AF and Ermanni P (2014) Aero-structural optimization of three-dimensional adaptive wings with embedded smart actuators. *Journal of Aircraft* 52(9): 1940–1951.

Molinari G, Quack M, Arrieta AF, et al. (2015) Design, realization and structural testing of a compliant adaptable wing. *Smart Materials and Structures* 24(10): 105027.

Molinari G, Quack M, Dmitriev V, et al. (2011) Aero-structural optimization of morphing airfoils for adaptive wings. *Journal of Intelligent Material Systems and Structures* 22: 1075–1089.

Monner HP, Riemenschneider J, Opitz S, et al. (2011) Development of active twist rotors at the German Aerospace Center (DLR). In: *Proceedings of the 52nd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Denver, CO, 4–7 April, AIAA 2011-1824.

Moslehi B, Black RJ and Faridian F (2011) Multifunctional fiber Bragg grating sensing system for load monitoring of composite wings. In: *Proceedings of the 2011 IEEE aerospace conference*, Big Sky, MT, 5–12 March.

Muhammad A, Nguyen QV, Park HC, et al. (2010) Improvement of artificial foldable wing models by mimicking the unfolding/folding mechanism of a beetle hind wing. *Journal of Bionic Engineering* 7: 134–141.

Munteanu E and Ursu I (2008) Piezo smart composite wing with LQG/LTR control. In: *Proceedings of the IEEE international symposium on industrial electronics ISIE 2008*, Cambridge, 30 June–2 July, pp. 1160–1165. New York: IEEE.

Nakamura N, Ogisu T, Yoneda H, et al. (2007) Impact monitoring of the aircraft composite structure using FBG sensor/PZT actuator hybrid sensor system. In: *Proceedings of SPIE industrial and commercial applications of smart structures technologies 2007*, San Diego, CA, 18 March, vol. 6527, p. 65270B. Bellingham, WA: SPIE.

NASA (2001) Available at: http://www.nasa.gov/centers/dryden/multimedia/imagegallery/Morph/ED01-0348-1.html#.UwYYWE3ivIU (accessed 10 June 2014).

Nespoli A, Besseghini S, Pittaccio S, et al. (2010) The high potential of shape memory alloys in developing miniature mechanical devices: a review on shape memory alloy mini-actuators. *Sensors and Actuators A: Physical* 158: 149–160.

Oates WS, Mauck LD and Lynch CS (2000) PZT piston driven hydraulic pump development. In: *Proceedings of the 2000 12th IEEE international symposium, applications of ferroelectrics*, Honolulu, HI, 21 July–2 August, pp. 733–736. New York: IEEE.

Oehler SD, Hartl DJ, Lopez R, et al. (2012a) Design optimization and uncertainty analysis of SMA morphing structures. *Smart Materials and Structures* 21: 094016.

Oehler SD, Hartl DJ, Turner TL, et al. (2012b) Modeling fluid structure interaction with shape memory alloy actuated morphing aerostructures. In: *Proceedings of SPIE industrial and commercial applications of smart structures technologies 2012*, San Diego, CA, 11 March, vol. 8343, p. 834305. Bellingham, WA: SPIE.

Okabe Y and Sugiyama H (2009) Shape-variable sandwich structure with SMA honeycomb core and CFRP skins. In: *Proceedings of SPIE active and passive smart structures and integrated systems 2009*, San Diego, CA, 8 March, vol. 7288, p. 728817. Bellingham, WA: SPIE.

Olympio KR and Gandhi F (2010) Zero Poisson's ratio cellular honeycombs for flex skins undergoing one-dimensional morphing. *Journal of Intelligent Material Systems and Structures* 21: 1737–1753.

Structures. Epub ahead of print 13 October. DOI: 10.1177/1045389X14554132.

O'Neill C and Burchfield J (2007) Kinetic ceramics piezoelectric hydraulic pumps. In: *Proceedings of SPIE industrial and commercial applications of smart structures technologies 2007*, San Diego, CA, 18 March, vol. 6527, p. 65270I. Bellingham, WA: SPIE.

Otsuka K and Wayman CM (1998) *Shape Memory Materials*. Cambridge: Cambridge University Press, pp. 1–19.

Paine JSN, Johns ME, Sesler JJ, et al. (2008) Linear high-force "step and repeat" piezoelectric motors. In: *Proceedings of the 39th aerospace mechanisms symposium, NASA Marshall Space Flight Center*, Huntsville, AL, 7–9 May.

Pankonien A and Inman DJ (2013) Experimental testing of spanwise morphing trailing edge concept. In: *Proceedings of SPIE active and passive smart structures and integrated systems 2013*, San Diego, CA, 10 March, vol. 8688, p. 868815. Bellingham, WA: SPIE.

Paradies R and Ciresa P (2009) Active wing design with integrated flight control using piezoelectric macro fiber composites. *Smart Materials and Structures* 18: 035010.

Park BJ, Fang FF and Choi HJ (2010) Magnetorheology: materials and application. *Soft Matter* 6: 5246–5253.

Park HC, Lee S and Kim KJ (2005) Equivalent modeling for shape design of IPMC (Ionic Polymer-Metal Composite) as flapping actuator. *Key Engineering Materials* 297–300: 616–621.

Pätzold A, Peltzer I, Nitsche W, et al. (2013) Active compliant wall for skin friction reduction. *International Journal of Heat and Fluid Flow* 44: 87–94.

Perkins DA, Reed JL Jr and Havens E (2004) Morphing wing structures for loitering air vehicles. In: *Proceedings of the 45th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Palm Springs, CA, 19–22 April, AIAA 2004-1888.

Philen M, Phillips D and Baur J (2009) Variable modulus materials based upon F^2MC reinforced shape memory polymers. In: *Proceedings of the 50th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Palm Springs, CA, 4–7 May, AIAA 2009-2116.

Pinkerton JL and Moses RW (1997) *A Feasibility Study to Control Airfoil Shape Using THUNDER* (Technical memorandum). Hampton, VA: NASA Langley Research Center.

Pitt DM, Dunne JP and White EV (2002) Design and test of a SMA powered adaptive aircraft inlet internal wall. In: *Proceedings of the 43rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Denver, CO, 22–25 April, AIAA 2002-1356.

Prawoto Y (2012) Seeing auxetic materials from the mechanics point of view: a structural review on the negative Poisson's ratio. *Computational Materials Science* 58: 140–153.

Prazenica RJ, Kim D, Moncayo H, et al. (2014) Design, characterization, and testing of macro-fiber composite actuators for integration on a fixed-wing UAV. In: *Proceedings of SPIE active and passive smart structures and integrated systems 2014*, San Diego, CA, 9 March, vol. 9057, p. 905715. Bellingham, WA: SPIE.

Previtali F, Arrieta AF and Ermanni P (2014a) Double-walled corrugated structure for bending-stiff anisotropic morphing skins. *Journal of Intelligent Material Systems and Structures*. Epub ahead of print 13 October. DOI: 10.1177/1045389X14554132.

Previtali F, Arrieta AF and Ermanni P (2014b) Performance of a three-dimensional morphing wing and comparison with a conventional wing. *AIAA Journal* 52(10): 2101–2112.

Probst TA, Kochersberger K, Stiltner B, et al. (2012) Smart material actuators as a means of UAV flight control. In: *Proceedings of the 50th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition*, Nashville, TN, 9–12 January, AIAA 2012-0486.

Ray CW and Batten BA (2012) Sensor placement for flexible wing shape control. In: *Proceedings of the 2012 American control conference*, Montréal, QC, Canada, 27–29 June, pp. 1430–1435.

Reed JL Jr, Hemmelgarn CD, Pelley BM, et al. (2005) Adaptive wing structures. In: *Proceedings of SPIE smart structures and materials 2005: industrial and commercial applications of smart structures technologies*, San Diego, CA, 6 March, vol. 5762, pp. 132–142. Bellingham, WA: SPIE.

Rodgers JP, Hagood NW and Weems DB (1997) Design and manufacture of an integral twist-actuated rotor blade. In: *Proceedings of 38th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference and adaptive structures forum*, Kissimmee, FL, 7–10 April.

Rodrigues G, Bastaits R and Preumont A (2010) Intelligent segmented deformable mirrors for adaptive optics. In: *Proceedings of ISMA2010 including USD2010*, Leuven, 20–22 September, pp. 4471–4483.

Rodriguez AR (2007) Morphing aircraft technology survey. In: *Proceedings of the 45th AIAA aerospace sciences meeting and exhibit*, Reno, NV, 8–11 January, AIAA 2007-1258.

Roglin RL and Hanagud SV (1996) A helicopter with adaptive rotor blades for collective control. *Smart Materials and Structures* 5: 76–88.

Roglin RL, Kondor S and Hanagud S (1994) Adaptive airfoils for helicopters. In: *Proceedings of 35th AIAA structures, structural dynamics, and materials conference*, Hilton Head, SC, 18–20 April, pp. 279–287. Reston, VA: AIAA.

Rose M, Unruh O and Haase T (2011) Vibration control of stiffened plates with embedded cavities using flat piezoceramic actuator devices. In: *Proceedings of the 18th international congress on sound and vibration*, Rio De Janeiro, Brazil, 10–14 July, pp. 1–8.

Rosén M and Hedenström A (2001) Gliding flight in a jackdaw: a wind tunnel study. *Journal of Experimental Biology* 204: 1153–1166.

Rossiter J, Takashima K, Scarpa F, et al. (2014) Shape memory polymer hexachiral auxetic structures with tunable stiffness. *Smart Materials and Structures* 23: 045007.

Roth B, Peters C and Crossley WA (2002) Aircraft sizing with morphing as an independent variable: motivation, strategies and investigations. In: *Proceedings of the AIAA's aircraft technology, integration, and operations (ATIO) 2002 technical*, Los Angeles, CA, 1–3 October, AIAA 2002-5840.

Sahu A, Banerjee T, Niyogi AG, et al. (2013) Active control of radiated sound from stiffened plates using IDE-PFC actuators. *International Journal of Acoustics and Vibration* 18(3): 109–116.

Saito K, Agnese F and Scarpa F (2011) A cellular kirigami morphing wingbox concept. *Journal of Intelligent Material Systems and Structures*. Epub ahead of print 5 August. DOI: 10.1177/1045389X11416030.

Sater JM and Crowe CR (2000) Smart air and space structure demonstrations: status and technical issues. In: *Proceedings of the 41st AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference and exhibit*, Atlanta, GA, 3–6 April, AIAA-2000-1625.

Schembri T, Tejedor S and Davis C (2013) Strain measurements using fibre Bragg gratings during full-scale structural testing of an F/A-18 centre barrel. *Key Engineering Materials* 558: 510–521.

Schultz MR (2005) A new concept for active bistable twisting structures. In: *Proceedings of SPIE smart structures and materials 2005: smart structures and integrated systems*, San Diego, CA, 6 March, vol. 5764, pp. 241–252. Bellingham, WA: SPIE.

Schultz MR and Hyer MW (2004) A morphing concept based on unsymmetric composite laminates and piezoceramic MFC actuators. In: *Proceedings of the 45th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Palm Springs, CA, 19–22 April, AIAA 2004-1806.

Sekine H, Fujimoto SE, Okabe T, et al. (2006) Structural health monitoring of cracked aircraft panels repaired with bonded patches using fiber Bragg grating sensors. *Applied Composite Materials* 13: 87–98.

Senthilkumar M (2012) Analysis of SMA actuated plain flap wing. *Journal of Engineering Science and Technology Review* 5(1): 39–43.

Shahinpoor M, Bar-Cohen Y, Simpson JO, et al. (1998) Ionic polymer-metal composites (IPMCs) as biomimetic sensors, actuators and artificial muscles—a review. *Smart Materials and Structures* 7: 15–30.

Shan Y, Philen M, Lotfi A, et al. (2009) Variable stiffness structures utilizing fluidic flexible matrix composites. *Journal of Intelligent Material Systems and Structures* 20(4): 443–456.

Shang BL, Song BF and Chang F (2008) New sensor technologies in aircraft structural health monitoring. In: *Proceedings of the 2008 international conference on condition monitoring and diagnosis*, Beijing, China, 21–24 April.

Shaw AD, Dayyani I and Friswell MI (2015) Optimisation of composite corrugated skins for buckling in morphing aircraft. *Composite Structures* 119: 227–237.

Simpson JO, Wise SA, Bryant RG, et al. (1998) Innovative materials for aircraft morphing. In: *Proceedings of SPIE smart structures and materials 1998: industrial and commercial applications of smart structures technologies*, San Diego, CA, 3–5 March, vol. 3326.

Sinn T and Barrett R (2010) Shape memory alloy post buckled precompressed (SMAPBP) actuator concepts and theory. In: *Proceedings of SPIE smart structures and materials + nondestructive evaluation and health monitoring*, San Diego, CA, 9 April, p. 764308. Bellingham, WA: SPIE.

Sirohi J and Chopra I (2002) Design and testing of a high pumping frequency piezoelectric-hydraulic hybrid actuator. In: *Proceedings of SPIE smart structures and materials 2002: smart structures and integrated systems*, San Diego, CA, 17 March, vol. 4701, pp. 552–569. Bellingham, WA: SPIE.

Smart Material Corp. (2014) Available at: http://www.smart-material.com/MFC-product-main.html (accessed 10 June 2014).

Sneed RC, Smith RR, Cash MF, et al. (2007) Smart-material based hydraulic pump system for actuation of a morphing wing. In: *Proceedings of 48th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Honolulu, HI, 23–26 April, AIAA 2007-1702.

Sodano HA, Park G and Inman DJ (2004) An investigation into the performance of macro-fiber composites for sensing and structural vibration applications. *Mechanical Systems and Signal Processing* 18: 683–697.

Sofla AYN, Meguid SA, Tan KT, et al. (2010) Shape morphing of aircraft wing: status and challenges. *Materials and Design* 31: 1284–1292.

Song GB, Ma N, Li LY, et al. (2011a) Design and control of a proof-of-concept active jet engine intake using shape memory alloy actuators. *Smart Structures and Systems* 7(1): 1–13.

Song YJ, Wei WL and Qu XG (2011b) Colorimetric biosensing using smart materials. *Advanced Materials* 23: 4215–4236.

Spadoni A and Ruzzene M (2007) Numerical and experimental analysis of the static compliance of chiral truss-core airfoils. *Journal of Mechanics of Materials and Structures* 2(5): 965–981.

Spangler RL Jr (1989) *Piezoelectric actuators for helicopter rotor control*. Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Steadman DL, Griffin SF and Hanagud SV (1994) Structure-control interaction and the design of piezoceramic actuated adaptive airfoils. In: *Proceedings of AIAA/ASME adaptive structures forum*, Hilton Head, SC, 21–22 April, AIAA 1994-1747, pp. 135–142. Reston, VA: AIAA.

Straub FK, Kennedy DK, Domzalski DB, et al. (2004a) Smart material-actuated rotor technology—SMART. *Journal of Intelligent Material Systems and Structures* 15: 249–260.

Straub FK, Kennedy DK, Stemple AD, et al. (2004b) Development and whirl tower test of the SMART active flap rotor. In: *Proceedings of SPIE smart structures and materials 2004: industrial and commercial applications of smart structures technologies*, San Diego, CA, 14 March, vol. 5388.

Sun J, Gao HL, Scarpa F, et al. (2014a) Active inflatable auxetic honeycomb structural concept for morphing wingtips. *Smart Materials and Structures* 23: 125023.

Sun J, Gong XB, Liu YJ, et al. (2013) Research on a variable camber wing with shape memory polymer skin. In: *Proceedings of 54th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Boston, MA, 8–11 April, AIAA 2013-1919.

Sun J, Liu Y and Leng J (2014b) Mechanical properties of shape memory polymer composites enhanced by elastic fibers and their application in variable stiffness morphing skins. *Journal of Intelligent Material Systems and*

Structures. Epub ahead of print 26 August. DOI: 10.1177/1045389X14546658.

Sun J, Xu YY, Chen YJ, et al. (2012) Spandex fiber reinforced shape memory polymer composites and their mechanical properties. *Advanced Materials Research* 410: 370–374.

Syaifuddin M, Park HC, Yoon KJ, et al. (2005) Design and evaluation of LIPCA-actuated flapping device. In: *Proceedings of SPIE smart structures and materials 2005: smart structures and integrated systems*, San Diego, CA, 6 March, vol. 5764, pp. 151–158. Bellingham, WA: SPIE.

Takahashi H, Matsumoto K and Shimoyama I (2009) Air pressure sensor for an insect wing. In: *Proceedings of 2009 IEEE 22nd international conference on micro electro mechanical systems (MEMS)*, Sorrento, 25–29 January, pp. 825–828. New York: IEEE.

Takahashi H, Matsumoto K and Shimoyama I (2010) Measurement of differential pressure on a butterfly wing. In: *Proceedings of 2010 IEEE 23rd international conference on micro electro mechanical systems (MEMS)*, Hong Kong, 24–28 January, pp. 63–66. New York: IEEE.

Takeda S, Aoki Y, Ishikawa T, et al. (2007) Structural health monitoring of composite wing structure during durability test. *Composite Structures* 79: 133–139.

Thill C, Etches J, Bond I, et al. (2008) Morphing skins. *Aeronautical Journal* 112: 117–139.

Thill C, Etches J, Bond I, et al. (2010) Composite corrugated structures for morphing wing skin applications. *Smart Materials and Structures* 19: 124009.

Thomas A (1996) The flight of birds that have wings and a tail: variable geometry expands the envelope of flight performance. *Journal of Theoretical Biology* 183: 126–134.

Tieck RM, Mohanchandra KP and Carman GP (2004) Smart material actuators for airfoil morphing applications. In: *Proceedings of SPIE smart structures and materials 2004: smart structures and integrated systems*, San Diego, CA, 14 March, vol. 5390, pp. 235–246. Bellingham, WA: SPIE.

Tzou HS, Lee HJ and Arnold SM (2004) Smart materials, precision sensors/actuators, smart structures, and structronic systems. *Mechanics of Advanced Materials and Structures* 11(4–5): 367–393.

Ueno T, Keat CS and Higuchi T (2007) Linear step motor based on magnetic force control using composite of magnetostrictive and piezoelectric materials. *IEEE Transactions on Magnetics* 43(1): 11–14.

Urban F, Kadlec J, Vlach R, et al. (2010) Design of a pressure sensor based on optical fiber Bragg grating lateral deformation. *Sensors* 10: 11212–11225.

Ursache NM, Isikveren AT and Friswell MI (2008) Technology integration for active poly-morphing winglets development. In: *Proceedings of SMASIS08, ASME conference on smart materials, adaptive structures and intelligent systems*, Ellicott City, MD, 28–30 October, SMASIS2008-496.

Vanderhoff A and Kim KJ (2009) Variable stiffness material and structural concepts for morphing applications. *Smart Materials and Structures* 18: 125014.

Vasista S and Tong LY (2013) Topology-optimized design and testing of a pressure-driven morphing-aerofoil trailing-edge structure. *AIAA Journal* 51(8): 1898–1907.

Vessonen I (2002) *Smart Materials and Structures: VTT Research Program 2000–2002, Espoo, Finland, 4th December 2002*. Espoo: Technical Research Centre of Finland.

Vigliotti A and Pasini D (2015) Analysis and design of lattice materials for large cord and curvature variations in skin panels of morphing wings. *Smart Materials and Structures* 24(3): 037006.

Vocke RD III, Kothera CS and Wereley NM (2012) Development of a span-extending blade tip system for a reconfigurable helicopter rotor. In: *Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Honolulu, HI, 23–26 April, AIAA 2012-1664.

Vocke RD III, Kothera CS and Wereley NM (2015) Development of a quasi-static span-extending blade tip for a morphing helicopter rotor. *Journal of Aircraft* 52(3): 1–13.

Vocke RD III, Kothera CS, Woods BKS, et al. (2011) Development and testing of a span-extending morphing wing. *Journal of Intelligent Material Systems and Structures* 22: 879–890.

Vos R and Barrett R (2010a) Pressure adaptive honeycomb: a new adaptive structure for aerospace applications. In: *Proceedings of SPIE sensors and smart structures technologies for civil, mechanical, and aerospace systems 2010*, San Diego, CA, 7 March, vol. 7647, p. 76472B. Bellingham, WA: SPIE.

Vos R and Barrett R (2010b) Pressure adaptive honeycomb: a novel concept for morphing aircraft structures. In: *Proceedings of 27th international congress of the aeronautical sciences (ICAS 2010)*, Nice, 19–24 September.

Vos R and Barrett R (2011) Mechanics of pressure-adaptive honeycomb and its application to wing morphing. *Smart Materials and Structures* 20: 094010.

Vos R, Barrett R and Romkes A (2011a) Mechanics of pressure-adaptive honeycomb. *Journal of Intelligent Material Systems and Structures* 22: 1041–1055.

Vos R, Barrett R, De Breuker R, et al. (2007) Post-buckled precompressed elements: a new class of control actuators for morphing wing UAVs. *Smart Materials and Structures* 16: 919–926.

Vos R, Scheepstra J and Barrett R (2011b) Topology optimization of pressure adaptive honeycomb for a morphing flap. In: *Proceedings of SPIE active and passive smart structures and integrated systems 2011*, San Diego, CA, 6 March, vol. 7977, p. 79771J. Bellingham, WA: SPIE.

Wang Q, Xu ZW and Zhu Q (2013) Structural design of morphing trailing edge actuated by SMA. *Frontiers of Mechanical Engineering* 8(3): 268–275.

Wei ZG and Sandström R (1998) Shape-memory materials and hybrid composites for smart systems: part I, shape-memory materials. *Journal of Materials Science* 33: 3743–3762.

Weiss P (2003) Wings of change: shape-shifting aircraft may ply future skyways. *Science News* 164(23): 359, 362, 365.

Wu R, Sun J, Chang ZZ, et al. (2014) Elastic composite skin for a pure shear morphing wing aircraft. *Journal of Intelligent Material Systems and Structures*. Epub ahead of print 13 March. DOI: 10.1177/1045389X14526796.

Xia YY, Bilgen O and Friswell MI (2014) The effect of corrugated skins on aerodynamic performance. *Journal of Intelligent Material Systems and Structures* 25: 786–794.

Yang LJ, Hsu CK, Ho JY, et al. (2007) Flapping wings with PVDF sensors to modify the aerodynamic forces of a micro aerial vehicle. *Sensors and Actuators A: Physical* 139: 95–103.

Yi JC, Zhang HS, Qiao XP, et al. (2012) Shape monitoring for wing structure using fiber Bragg grating sensors. In: *Proceedings of the 2012 IEEE fifth international conference on advanced computational intelligence (ICACI)*, Nanjing, China, 18–20 October, pp. 1032–1036. New York: IEEE.

Yin WL, Fu T, Liu JC, et al. (2009) Structural shape sensing for variable camber wing using FBG sensors. In: *Proceedings of SPIE, sensors and smart structures technologies for civil, mechanical, and aerospace systems*, San Diego, CA, 30 March, vol. 7292, p. 72921H. Bellingham, WA: SPIE.

Yin WL, Sun QJ, Zhang B, et al. (2008) Seamless morphing wing with SMP skin. *Advanced Materials Research* 47–50: 97–100.

Yokozeki T, Sugiura A and Hirano Y (2014) Development of variable camber morphing airfoil using corrugated structure. *Journal of Aircraft* 51(3): 1023–1029.

Yokozeki T, Takeda SI, Ogasawara T, et al. (2006) Mechanical properties of corrugated composites for candidate materials of flexible wing structures. *Composites Part A: Applied Science and Manufacturing* 37: 1578–1586.

Yoon KJ, Setiawan H and Goo NS (2006a) Design of elevator control surface actuated by LIPCA for small unmanned air vehicle. In: *Proceedings of SPIE smart structures and materials 2006: smart structures and integrated systems*, San Diego, CA, 26 February, vol. 6173, p. 61730D. Bellingham, WA: SPIE.

Yoon KJ, Setiawan H, Nguyen NT, et al. (2006b) Development of elevator control surface for small air robot using piezoceramic actuator. In: *Proceedings of the 2006 IEEE international conference on robotics and biomimetics*, Kunming, China, 17–20 December, pp. 835–839. New York: IEEE.

Yu K, Yin WL, Sun SH, et al. (2009) Design and analysis of morphing wing based on SMP composite. In: *Proceedings of SPIE industrial and commercial applications of smart structures technologies 2009*, San Diego, CA, 8 March, vol. 7290, p. 72900S. Bellingham, WA: SPIE.

Zareie S, Zabihollah A and Azizi A (2011) Buckling control of morphing composite airfoil structure using multi-stable laminate by piezoelectric sensors/actuators. In: *Proceedings of SPIE behavior and mechanics of multifunctional materials and composites 2011*, San Diego, CA, 6 March, vol. 7978, p. 79781Z. Bellingham, WA: SPIE.

Zhang P, Zhou L and Qiu T (2012) Design and application of cross-shaped cellular honeycombs for a variable camber wing. *Journal of Aircraft* 49(5): 1451–1459.

Zhang P, Zhou L, Cheng W, et al. (2014) Conceptual design and experimental demonstration of a distributedly actuated morphing wing. *Journal of Aircraft* 52(2): 452–461.

Zhao J, Niu J, McCoul D, et al. (2015) A rotary joint for a flapping wing actuated by dielectric elastomers: design and experiment. *Meccanica* 50(11): 2815–2824.