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A Review of Novel Approaches to Improve Aerodynamic Performance of Modern Aircraft

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Abstract

Due to the increasing demands of promoting the efficiency and aerodynamic performance of modern aircraft, apart from conventional optimization approaches, morphing techniques are seen as an alternative approach to achieve a better aerodynamic performance since seamless deformation becomes available for different flight conditions. Besides, a novel design of a blended wing aircraft also has a high potential to replace traditional passenger aircraft because this design integrates the fuselage and wings so that the fuselage can also generate lift. The main goal of this study is to review the basic properties and the applications of two morphing materials, namely shape memory alloy (SMA) and piezoelectric material, and the design concepts of blended wing body (BWB) aircraft. Furthermore, the limitations of these novel approaches are also discussed such as their fatigue behavior and unstable performance, and most of these techniques can only be applied to smaller size aerial vehicles in the preliminary stage.

Keywords

Morphing; Shape memory alloy; Piezoelectric material; Blended wing body aircraft; Optimization

Introduction

World air traffic has been increasing over the last decades and researchers are keen on finding new ways to enhance aerodynamic performance for different situations and save fuel costs ("Current Market Outlook", 2022). Methods of doing optimizations based on the standard baseline model by using models and techniques with higher fidelity are significant, while the optimized wing shape for all stages in a flight which includes take-off, cruise, and landing is different (Mader and Martins, 2013). To be

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more specific, a high lift is a dominant condition at low speeds and high angles of attack during take-off and landing, however, parasite drag has to be reduced at high cruise speeds with low angles of attack. For instance, a high wing camber is well-performed at low speeds and it generates a lot of lift due to a higher velocity of downwash. On the opposite, a high wing camber will shift the separation point forwards and induce form drag to a large extent.

Traditional aircraft utilize hinged control surfaces which include ailerons, flaps, and rudders to alter their aerodynamic behaviors. These conventional designs inevitably introduce discontinuities in the profile that cause undesired vortices and induce drag. To eliminate these gaps, one potential solution is morphing wings, which means deforming the structure as a whole seamlessly, and the key to enabling deformation is to find a suitable novel material that is easy to actuate to form the desired structure while maintaining the capability of withstanding sufficient loads. There are many types of morphing materials including a shape memory alloy (SMA) and piezoelectric material. However, most of them still have some limitations in some particular aspects and scientists are still finding new methods to reinforce their properties by changing internal structures or combining them with other materials. Typically, most of these morphing skin materials are used or tested in smaller air vehicles like unmanned aerial vehicles (UAVs) (Sun, Guan, Liu & Leng, 2016).

Another novel practice to increase the lift-to-drag ratio and improve efficiency is to replace with the blended wing body(BWB) aircraft. In traditional aircraft, the fuselage creates a lot of unwanted parasite drag without generating lift, while the BWB design integrates all of the conventional components as a whole wing-shape structure to increase the lift-to-drag ratio (Merino-Martinez, 2014). However, the number of researches made in this area is very limited and there are many difficulties in the design phase such as its stable performance.

This paper aims to review different methods to reinforce aerodynamic performances including traditional optimization techniques, morphing approaches using SMA and piezoelectric material, and the idea of blended wing body(BWB) aircraft.

Conventional Approaches

For traditional aircraft, Mader and Martins analyzed the optimization method of the overall performance of an aircraft under various structural and stability constraints in subsonic and transonic regimes (Mader and Martins, 2013). A Python-based optimization framework pyOpt is used to deal with nonlinearly constrained optimization problems, along with pyACD, pyCSG, and Computational Fluid Dynamics (CFD), which enable geometry modeling including conceptual design description and comprehensive view of the sweep, taper, twist, span, and chord respectively. In this paper, the root bending moment is used as an estimation to measure the structural performance of the wing; static stability is accessed by static margin and control anticipate parameter (CAP), getting from frequency and damping ratio is used to evaluate dynamic stability. As a large number of variables and constraints are presented in this study, coupling the disciplines incorporating geometry, aerodynamics, flight dynamics, and structure is necessary when using adjoint methods. The results show in the baseline and twist-only case, that all the parameters vary in a qualitatively intuitive manner and the observed values are within the percentage accuracy of the real value as the Mach number increase from 0.5 to 0.7 to

0.85. Therefore, the accuracy of the measurement techniques is proved in a persuasive way. What's more, the results indicate the optimum wing shapes under static and dynamic stability constraint cases and sweep is crucial in all situations when shape variables are added. The degradation of overall performance in the subsonic and the lower end of the transonic regimes is negligible, but this declination becomes inevitable in the transonic regimes.

SMA Properties and Its Morphing Applications

Shape memory alloys (SMAs) are one of the most common morphing materials due to their compliance, high loadability, and power density (Barbarino et al., 2014). The two most widely-used SMAs are copper-aluminum-nickel and nickel-titanium, and SMAs exist in two solid phases: the austenite state and the martensite state. Thermodynamically, austenite favors in high temperatures whereas martensite favors in low temperatures and it can be obtained by high loading, the two phases can transform from one to another through heating and cooling. Hence, we can define these critical temperatures for SMAs: Mf < Ms < As < Af < Md, where M stands for martensite, A stands for austenite, s means starting temperature, f means final temperature, and Md is the temperature that SMAs are permanently deformed. These transition temperatures increase when applying external loads because more energy is required to deform the structure.

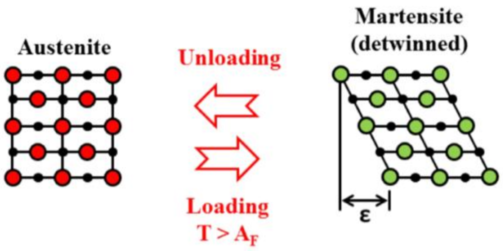

Figure 1. Shape memory effect (Barbarino et al., 2014)

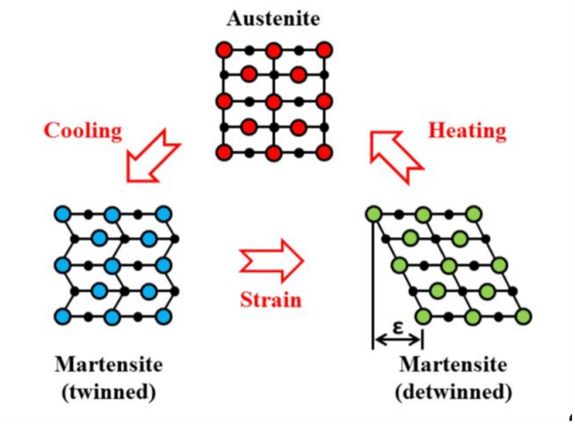

Figure 2. Pseudo-elastic effect (Barbarino et al., 2014)

Figures 1 and 2 show the two main characteristics of SMAs which are the shape memory effect (SME) and pseudo-elastic effect. SME happens in the transformation from austenite to martensite. Internal strain energy is introduced during cooling so the martensite phase forms many twins in order to reduce this energy and the twins are known as the “self-accommodating twinning”. However, when loads are applied, the self-accommodating twins provide an easy path to get detwinned without damaging its microstructure which means the relative positions of atoms and their neighbors stay the same. Finally, the alloy can completely recover from this deformation when increasing the temperature and this cycle is how SME works.

The pseudo-elastic effect takes place when a suitable load is applied to the austenite phase and at Af < T < Md, the alloy will go directly from austenite to martensite phase and get detwinned. But this state is not stable, so once the alloy is unloaded and the load reaches the critical stress for austenite, the reversible mechanism takes place again as discussed before.

Generally, the SMA shows excellent performance to be applied as actuators. The yield stress for Ni and Ti ones can reach 500MPa, and another advantage is the high level of plastic strain recoverability and the strain is up to 8% without permanent damage. On the other hand, one of its main limitations is its asymmetric actuation as its deactivation time is far longer compared to its actuation time.

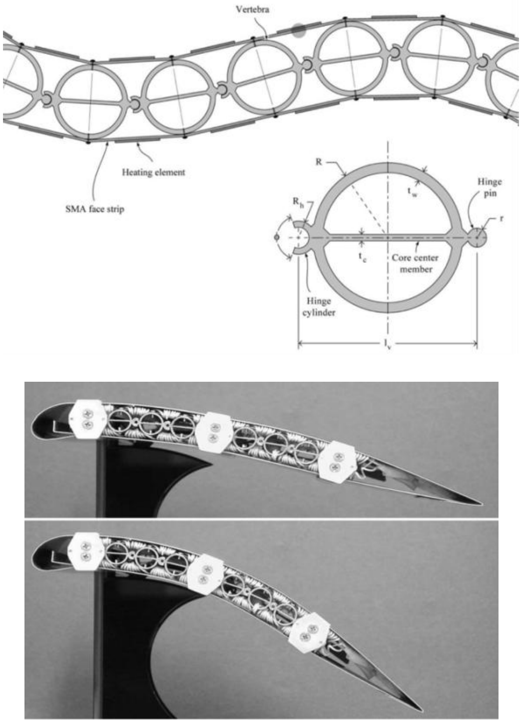

Figure 3. The 'vertebrate' structure of the actuator. (Elzey et al., 2003)

Morphing using SMA has been under research for more than two decades. Elzey et al. designed a bio-inspired, fully reversing, shape morphing structural morphing actuator by using cellular flexible cores sandwiched between SMA face sheets (Elzey et al., 2003). This design is foreseen to be applied in aero and hydro control surfaces (e.g. morphing wing shapes for aircraft). The two-way shape memory effect is used which means the material remembers two different shapes in both of its two solid phases, and this prevents the participation of the biasing force (elastic restoring force). To get a more specific look at the actuator, the core has a 'vertebrate' structure (shown in figure 3) which consists of a series of tubular elements linked together by cylinder-and-sleeve joints, so that the bending resistance is really small. The SMA face stripes are positioned on the surface between each tubular element, where the desired contraction can be obtained by heating the strips selectively on either side of the plane. Additionally, an expression of moment and curvature capability is derived by using the geometric parameters and the material properties (Young's modulus for SMA is 90 GPa, and the yield strength is 550 MPa). Finally, a prototype control surface is constructed, the SMA wires are heated by a coiled resistance heating element (plastic coated wire) with four heating circuits in a given dimension, and the temperatures are monitored by thermocouples to ensure the critical temperatures are reached before heating and cooling.

To focus more on aerodynamic performance, Galantai et al. analyzed the deformable wing area structure by changing the spars and ribs for unmanned aerial vehicles (UAVs) (Galantai et al., 2011). The objective of this research is to reduce drag at high speeds by decreasing the surface area and hence, the sweep is added. SMA actuators are uniformly distributed along the cellular core spars in order to ensure vertical rigidity and horizontal flexibility. And a shearing approach is implemented between the ribs and spars so that when spars are actuated, the wing is able to sweep backward and area planform is reduced. Basic parameters including lift, drag, lift-to-drag ratio, and wing loadings are evaluated. It is concluded that power requirements based on a sample similar to AAI Shadow 200, are decreased by 9%～12% at its maximum speed, and therefore, this significant improvement indicates the high potential for sweep morphing.

By using stronger computational power, Cees Bil et al. evaluated the aerodynamic performance of a wing by using SMA actuators to deform the leading edge under different conditions by using CFD and wind tunnel tests (Cees Bil et al., 2013). The effectiveness of different controllers and the power required for the SMA actuators under aerodynamic load were also analyzed. The study focused on UAVs because UAVs are designed to operate for a long period, better efficiency means less fuel consumption and it enables longer flights. The SMA actuators are placed near the leading edge and the 3D finite element (FE) method is used to analyze the force required to deform the wing to an optimal configuration of the SMA wires and the skin material that matches the optimum lift-to-drag ratio at a specific angle of attack by varying the camber. The SMA wires in this model are FLEXINOL wires and multiple wires are bundled together to increase the pull force of actuators without sacrificing actuation time. In addition, a controller is required due to the nonlinearity of SMA actuation, and it is found that the PID with an anti-windup compensator shows the most accurate results and the fastest response time by comparing three different types of controllers. The overall performance indicates that the greatest improvement in the lift-to-drag ratio is about 15% at angles of attack between 0 ~ 15 deg and the power requirement increases significantly at high angles of attack.

Properties of Piezoelectric Material and Its Applications

As the electric charge accumulates in the piezoelectric materials, the piezoelectric effect is caused by the reconfiguration of the dipole-inducing surrounding or by the re-orientation of molecular dipole moments under the influence of external stress. This linear electromechanical process is also reversible, which means mechanical strain would be generated by applying an electric field and that's how this smart material generates controllable deformation. However, its strain output is limited, for instance, one of the most commonly used piezoelectric ceramics, lead zirconate titanate (PZT) will deform by about 0.1% of its original dimension when an external electric field is applied. To produce a larger strain, piezoelectric fibers can be mixed with resin to produce piezoelectric composites including active fiber composite (AFC) and macro fiber composite (MFC). MFC is advanced from AFC, and it is a type of piezoceramic material that offers structural flexibility and high actuation authority (Sun, Guan, Liu & Leng, 2016).

Bilgen et al. first successfully demonstrated the effectiveness of applying piezoelectric actuators in morphing UAVs (Bilgen et al., 2009). Two MFC patches, placed at the root chord of the wings, are used to create the deformation of camber on a swept, flying wing platform, which causes pitch and roll movement by either actuating them in the same direction or in opposition. Modifications are made based on their baseline model. To increase the stiffness, a thin glass layer is bonded to the leading edges of both of the wings in the spanwise direction. To increase the strain output of the camber, the trailing edges of the wings are cut in the chordwise directions, so that less constraint of MFC actuation is presented despite the introduction of the unwanted discontinuity caused by the cut. Additionally, a high voltage (up to 1500V) has to be supplied due to the properties of MFC. Wing tunnel experiments are carried out to evaluate lift, drag, roll and pitch characteristics for four operational conditions: 'No Actuation,' symmetrically 'Both Wings' actuated, and the two asymmetric cases, 'Right Wing' only, and 'Left Wing' only. Maximum Cl of 1.06 is observed corresponding to a maximum L/D of 4.79. The non-dimensional rolling velocity of 0.052 was calculated and a 145% increase in roll moment actuation is achieved due to the modifications. Finally, a 15-minute flight test has proceeded and relatively stable aerodynamic performance and data recorded during the flights prove the reliable control authority and the feasibility of high voltage actuation in UAVs. Overall, the limitations of this study are the discontinuities on the surface and the lack of consideration of aeroelasticity, where aerodynamic loads may be utilized to generate greater force outputs for further developments.

By upgrading their previous structure, Bilgen et al. presented a novel, advanced, high-load output, bidirectional variable-camber airfoil by using MFC (Bilgen et al., 2010). This design employs two active surfaces and each surface is fabricated by four MFC 8557-P1 actuators, and a compliant box sandwiched between the two laminates, which helps to maintain the minimum thickness of the airfoil structure, while it allows free sheer motion caused by the camber variation. It is predicted that the maximum theoretical L/D is 42.6 for the 10% thick airfoil at 1300V by using XFOIL. The detailed wind tunnel experiments are carried out, and the results show that there is no observable deformation caused by the aerodynamic loads and the hysteresis effect can be utilized to carry external loads without consuming any power. A change of 1.54 in the lift coefficient for the peak-to-peak input is conducted at a freestream velocity of 15 m/s, which indicates the significant usefulness of camber deformation. A maximum L/D ratio of 13.4 is achieved. It can be concluded that the high output force and reduced input moments presented in this airfoil, provide significant potential for applications that needs to handle high dynamic pressure and symmetric deflection like UAVs and MAVs.

Bilgen and Friswell investigated the static-aeroelastic effectiveness of a variable-camber tapered morphing wing by using MFC actuators (Bilgen and Friswell, 2013). The main problems in the previous studies are the insufficiency of the aerodynamic effect due to the limited strain output of piezoelectric materials, and finding an optimum structure with low mass concentration and less number of discontinuities caused by discrete surfaces. To get a continuous, inextensible surface camber-variable wing, different curvatures of the upper and lower surfaces must be maintained. Thus, the top, leading-bottom, and trailing-bottom piezoelectric (PZT) actuators are established. Additionally, continuity is also guaranteed by a single substrate that wraps around the wing shape and 10 MFC bimorphs are sandwiched between the lower and upper surfaces. For the computing part, GA (genetic algorithm) optimization techniques are selected to approach the global optimum over a huge number of generations and runs, and the advantages of these optimization solutions are their capability for both maximum performance and FSI (fluid-structure interaction) problems. For its static-elasticity, the FSI problems can be solved by using a MATLAB -based, panel method software: XFOIL, and all the pressure-induced parameters such as lift and drag can be measured by iteration 5 times. Finally, concluded from the experimental results by using a wind tunnel, the voltage-induced peak-to-peak change in lift coefficient due to piezoelectric actuation is relatively small at a maximum free stream velocity of 22.8 m/s and a maximum Reynolds number of 251,000. Therefore, the reliability of aeroelasticity is proved by the small variations of lift coefficient at this transonic Reynolds number regime, however, further investigations need to proceed for a higher Reynolds number regime.

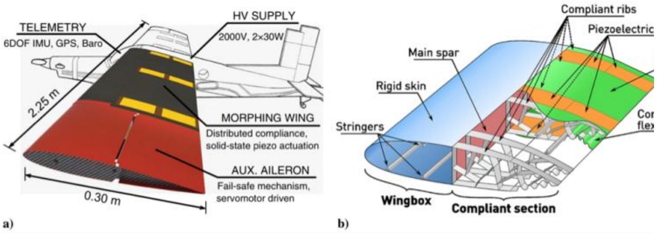

Figure 4. a) Modified UAV fitted with the baseline individual smart morphing wings. b) Illustration of the smart morphing wing concept. (Henry et al., 2019)

Because of the limitations in structural efficiency analysis and lightweight morphing structures for maximizing aerodynamic performance, Henry et al. investigated the optimal structural parameters of distributed piezoelectric actuators on a compliant morphing wing in terms of maximum achievable rolling moment and flutter speed, under aeroelastic loads (Henry et al., 2019). The baseline model (shown in figure 4) includes three sets of piezoelectric elements on each wing, which consist of two M-8557-P1 patches on the upper side and one on the lower side for each element. Carbon fiber–reinforced polymer (CFRP) is chosen for the leading and trailing edge skin due to its stiffness and lightweight characteristics. A corrugated glass fiber–reinforced polymer (GFRP) panel is placed on the lower side of the trailing edge to make the structure more compliant while enhancing the stiffness in the spanwise direction. During the two-stage multidisciplinary optimization process, the width of the piezoelectric layer (Wp), the thickness of the piezoelectric layer (Tp), and the thickness ratio (β) are input as the main parameters, whereas the first stage only studies thickness variables with fixed Wp and the second stage will include all these three variables. For each stage, static aeroelasticity is evaluated by the FE model to test its mechanical response, and the maximum load factor condition and roll moment coefficient are estimated by different actuation conditions. Additionally, dive speed is limited to 75% of flutter speed based on the quasi-steady approximation, and the final evaluations for a rolling moment and dive speed are done by sequential response surface technique. The competing nature of these parameters shows the imperfection of optimizations, but results perform high potential in optimizing any of these single aspects.

The Concept and the Design of BWB

A blended wing body (BWB) aircraft is a fixed-wing aircraft integrating the fuselage with the wings as a whole structure. Compared to the traditional flying wing, the main advantage of the BWB aircraft is that the whole structure is able to generate lift whereas the fuselage in a conventional aircraft does nothing to enhance aerodynamic performance. Moreover, BWB can reduce wetted area and hence, the accompanying form drag. Therefore, BWBs have a high potential to take the position of conventional aircraft to save fuel costs to a large extent. However, the main drawbacks that hinder the BWBs to be applied as passenger aircraft are their terrible passenger experiences due to lack of stability and the limitation of the number of emergency exits (Merino-Martinez, 2014).

Merino-Martinez designed a baseline model of a tailless BWB aircraft, and they studied its optimal control surface design by analyzing its aerodynamic behaviors, especially stability and control features through a computing approach (Merino-Martinez, 2014). CEASIOM (Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods) is adopted which is a multidisciplinary tool that provides high fidelity during the beginning of the product definition and CPACS (Common Parametric Aircraft Configuration Scheme) is implemented to design the geometry of the aircraft including all of its components because

CPACS can be used to design unconventional aircraft without limitations during modeling. Additionally, an aerodynamic database with forces and moments for flight dynamic analysis is generated by using TORNADO, which is the most appropriate method in the ABM-CFD. This tool is based on the potential Vortex Lattice Method(VLM), for steady and unsteady low-speed cases. The characteristics of stability including modes of motion are simulated by SDSA (Stability and Control) which is a 6-DoF simulation. All these techniques have relatively high fidelity during this preliminary design stage because the cost of the redesign is high. The overall performance shows a 12% reduction in the area of the control surface compared to the baseline model (Wortmann fx 60-126 airfoil) and the operating lift-to-drag ratio is significantly increased to 25~35 at small angles of attack which is remarkably higher than Boeing 747 (Boeing 747's lift-to-drag ratio is approximately 17). Besides, all of the static and dynamic stability parameters are satisfied but the Dutch rolls and spiral modes are in limit to be unacceptable due to their dependency on the rudder.

Lyu and Martins provided an alternative method to perform optimized trade-offs for BWBs in transonic regimes under the following constraints: geometry constraints, trim constraints, static margin constraints and lift constrain (Lyu and Martins, 2014). RANS CFD is used where the RANS equations are time-averaged equations of motions in flow fields, they are especially useful in turbulent flow so that the nonphysical features in Euler CFD will be eliminated, and it is worth mentioning that SNOPT (sparse nonlinear optimizer) is implemented for the whole optimization part due to its capability of solving large-scale nonlinear optimization problems with thousands of constraints and variables. According to the results, shock waves are greatly weakened, and minimum drag is achieved by only adding shape and twist variables. Although it is impractical in this case, the lift distribution is close to the elliptical shape. In the second case, a 2.3% drag penalty is created after adding the trim constraints, this sacrifice is minimized by shifting the MAC aft. In case 3, the optimized trade-off between performance and stability is made by adding the static margin constraint, however, designers have to consider the bending moment constraint to make the aircraft robust enough in the following cases. Finally, platform design variables, including sweep and span, are added to enable greater flexibility so the overall performance is enhanced to a further extent. (However, this research is still limited by the contradictory requirements during different stages of flight by compromising the parameters based on the baseline model in the first stage.) In conclusion, this study gives a useful and practical approach to optimizing BWB by adding these constraints one after another.

Arokkiaswamy and Alen compared the aerodynamic performance of a BWB with the conventional transport aircraft by a wind tunnel (Arokkiaswamy and Alen, 2019). This experimental approach greatly reduced the time for shape optimization. The key dimensions of a basic configuration of BWB (called BWB1) and the two most typical transport aircraft, Boeing 747 and 787, are evaluated both experimentally (using a wind tunnel) and numerically (using CFD) in turbulent flow conditions so that the excellence of BWB can be exhibited directly and the accuracy of the experimental approach is ascertained as well. By looking at the results, the improvements in lift-to-drag ratio, maximum lift coefficient, and minimum drag coefficient are 38%, 21%, and 26% respectively through experimental methods, where the results of the two practices are within the limits of accuracy. Further development of the optimized configuration experimental investigation is planned for better performance characteristics.

Limitations of These Smart Materials and Potential Solutions

SMAs are widely selected for manufacturing actuators in morphing wings due to their unique ability to recover large inelastic strain and high power-to-weight ratio. The actuation of SMA is usually done by fast Joule heating and the deactivation occurs by free convective heat transfer to the ambient environment, which is much slower. Consequently, the SMA actuation is typically asymmetric and its limited frequency is one of the main drawbacks(Huang et al., 2019). For those UAVs and MAVs flying in subsonic regimes, Abadie et al. presented a microscopic SMA ohm-shape module that provides some constructive improvements for wings with thin profile thickness (Abadie et al., 2002). This structure uses the Peltier effect and Thomson effect to control the whole system, hence increasing the rate of heating and cooling processes to a frequency of 1 Hz with a large angle of deflection.

Huang et al. presented a study to reduce the cooling time of SMA actuators in order to increase their bandwidth, they utilized the mismatch of strain between austenite and martensite phases, and the high thermal conductivity of the elastomers with silicon layers that sandwich the SMA wires to produce a fast dynamic response while ensuring stiffness. This research realizes the transition between actuated and unactuated states with a frequency of 0.3 Hz and it generates a force of 0.2 N in 0.15 s. Although this technique was designed for soft robots, it has the potential to be applied to UAVs in complex terrain.

Additionally, cyclic loading (both mechanical and thermal) will cause the SMA to lose the ability to undergo a reversible phase transformation due to the buildup of accommodation slip dislocations. According to the results presented by Lagoudas et al., thermomechanical transformation fatigue life can be expressed by a function of the applied stress, the material processing, and the percentage of transformation (Lagoudas et al., 2009). Apparently, partial transformation, lower stress, and transformation strain amplitudes help to improve its fatigue behavior. In real cases rather than laboratory conditions, methods of elongating the fatigue life of SMA were investigated by Mammano and Dragoni. For instance, putting a limit to the maximum strain in constant stress situations can increase fatigue life to a great extent. However, the exposure to constant strain is very detrimental to its fatigue life, and this study shows a preliminary test that a remarkable reduction in fatigue limit is observed under linear stress-strain variation (39 MPa for each percent strain) with limited maximum strain (4%) (Mammano and Dragoni, 2013).

Piezoelectric material is also not perfect. Due to the limited strain output of piezoelectric materials, enabling sufficient deformation for different fluid conditions remains a challenging task. (X. Chen et al., 2022) presented an alternative approach to generating considerable deformation of a lightweight MFC actuated winglet. Instead of pursuing a large strain output by changing the composition of the material itself, a hinged structure embedded between the wing and winglet is developed by placing the MFC bending actuator in the wing part so that a flexible rotational 16-degree deformation of the cant angle in high wind speed is realized. Moreover, a DC-DC converter devise and a 20M ohm resistor are implemented to transfer the 0-5V input voltage to 0-1500V which enables the actuation with a tiny power of 0.33W. By utilizing the FE model and optimizing its geometric parameters, a nearly linear relationship between the input voltage and the bending angle is obtained. Although this research did not solve the problems from the angle of the material itself, a significant improvement in the lift-to-drag ratio by up to 11.9 of the winglet is achieved, and the feasibility and reliability of this study are confirmed in the wind tunnel test. However, this structure might not be compatible with a variable-camber or a twist morphing structure because of its rotational deforming mechanism.

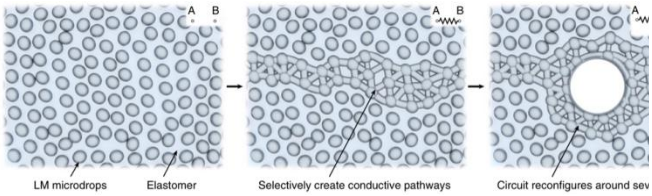

Figure 5. The illustration of the self-healing mechanism. (Markvicka et al., 2018)

Alternatively, a state-of-the-art material may become a suitable candidate for morphing aircraft and it was discovered and analyzed by Markvicka et al.. This material is made up of droplets of Ga-based liquid metal (LM) alloy embedded in a silicone elastomer. It performs excellent electrical conductivity, electrical stability, and resilience as soon as it is actuated since conductive pathways can be created by these droplets selectively despite the severe damage (shown in figure 5), while it is an insulator in the un-actuated condition (Markvicka et al., 2018). The reliability of its fatigue behavior is confirmed since when 40% tensile strain is applied in cyclic loading, no electrical conductivity loss is observed, and this outstanding performance is mainly due to its self-healing effect. Moreover, this material is capable of certain types of data transmission, so it can be acted as a sensor for detecting fatigue and measuring ambient stress, and no external electronics for damage detection are needed. Therefore, this novel material may be applied on UAVs or MAVs for military prospects due to its resistance to punctures. However, the main limitation is its robustness since it can only withstand compressive loads to 35 N (pmax = 1.32 MPa) and it is evident that this is not sufficient for faster flights with high aerodynamic loadings. Therefore, there's still a long way to go for this novel material to show its unique properties in morphing industries.

The Plane as a Whole

For those novel morphing techniques and structures, idealizing all the factors and putting the manufacture of the entire aerial vehicles at an industrial level is never an easy task since all the indicators need to be satisfied and ensure no degradation of performance observed in extreme conditions after repeated multidimensional testings. Due to the limitation of different morphing materials and their unique properties, most of the previous studies still focused on monitoring and enhancing some specific properties of a type of material for a part of the wing such as a variable camber, together with a preliminary analysis of its local performance.

However, a high-fidelity overall optimization should be taken into consideration just as how conventional aircraft were optimized in the past decades. For the morphing wings, the geometry of its internal structure is also a significant factor since a reduced actuation of the embedded multi-stable elements is study-worthy without compromising shape adaptability. Recently, Schlup et al. presented a comprehensive investigation of the Metamorph-2 (XM-2), a fully morphing UAV with twisting wings and variable-camber tail stabilizers (Schlup et al., 2021). Polyurethane foam with a wing gearbox is implemented for a 15 deg twisting motion on either side. In the horizontal and vertical stabilizers, active ribs are made up of Plasticized Copolyamide Thermoplastic Elastomers (PCTPE) which featured SMA wires actuators in a similar way. MATLAB applications were involved in the geometric design phase, and high-fidelity 2D and 3D CFD analysis and FE analysis were applied to confirm these design decisions including aerodynamic load distribution, a lift-to-drag ratio under different angles of attack, and Reynold's number variables. This study is focused on the full-scale model instead of the morphing wings only, and further flight tests would be taken.

Moreover, the morphing techniques may even be implemented on BWB aircraft in the future. Since the research of both morphing wings and the design of BWBs are in their preliminary stages, the integration between these two fields may open a brand new door for the prospective development of aerial vehicles. Although huge improvements in overall efficiency might be achieved, establishing an applicative model based on BWB aircraft optimization and integrating a diverse range of multidisciplinary parameters are still challenging and time-consuming. As most the BWBs are designed for traveling in transonic or even supersonic regimes, these smart materials may not be capable of withstanding such high aerodynamic loadings. Besides, morphing the fuselage itself is important since it is also responsible for generating lift as a part of the wing, and this task is unprecedented. By solving these technical issues, morphing BWBs may become the mainstream development tendency of modern aircraft.

Conclusion

In this review, novel approaches to improve aerodynamic efficiency are reviewed, including morphing by using shape memory alloy and piezoelectric material, and the design of blended wing body aircraft. Basically, the development of all of these methods undergoes a preliminary design phase, a further optimization stage (similar to conventional optimization under different constraints), and finally, they may be put into an industrial level until these techniques become mature enough. Primarily, the majority of these studies focus on camber morphing and sweep morphing since they are relatively more effective in improving their aerodynamic efficiency. Additionally, wing area morphing, twist morphing, and winglet morphing are also reviewed. Combining these morphing techniques will be beneficial as long as these variations of aerodynamic properties are necessary for specific usage.

The mechanisms and the main characteristics of shape memory alloy and piezoelectric material are discussed. For SMA morphing actuators, the shape memory effect is primarily used to enable the ability to recover from their original shape at certain characteristic temperatures. Besides, the pseudo-elastic effect prevents permanent damage due to the high level of plastic strain recoverability. For piezoelectric actuators, the transformation between mechanical energy and electrical energy generates deformation.

However, the SMA and the piezoelectric material are still not suitable for the production of commercial aircraft and most of the studies only focus on their performance on smaller size UAVs. This is primarily because of their limitations and the lack of general constitutive models for aerospace companies. Specifically, the asymmetric heating and cooling time of SMA results in the lack of frequency and fast response; and the inevitable internal slip dislocations cause a decrease in life span. What’s more, the limited strain output and the high operating actuation voltage of piezoelectric material are still unsolved.

Furthermore, the design of BWB provides another way of thinking to improve aerodynamic performance by integrating the fuselage and the wings. However, the lack of stability and security still left a great problem to be solved. In the future, utilizing morphing techniques on BWB will have a chance to create a significant improvement to a great extent.

Conflict of Interests: the author has claimed that no conflict of interests exists.

References

1. Abadie, J., Chaillet, N., & Lexcellent, C. (2002). An integrated shape memory alloy micro-actuator controlled by thermoelectric effect. *Sensors And Actuators A: Physical*, *99*(3), 297-303. DOI: 10.1016/s0924-4247(01)00832-9
2. Barbarino, S., Saavedra Flores, E., Ajaj, R., Dayyani, I., & Friswell, M. (2014). A review on shape memory alloys with applications to morphing aircraft. *Smart Materials And Structures*, *23*(6), 063001. DOI: 10.1088/0964-1726/23/6/063001
3. Bil, C., Massey, K., & Abdullah, E. (2013). Wing morphing control with shape memory alloy actuators. *Journal Of Intelligent Material Systems And Structures*, *24*(7), 879-898. DOI: 10.1177/1045389x12471866
4. Bilgen, O., Kochersberger, K., & Inman, D. (2009). Macro-fiber composite actuators for a swept wing unmanned aircraft. *The Aeronautical Journal*, *113*(1144), 385-395. DOI: 10.1017/s0001924000003055
5. Bilgen, O., Kochersberger, K., Inman, D., & Ohanian, O. (2010). The novel, Bidirectional, Variable-Camber Airfoil via Macro-Fiber Composite Actuators. *Journal Of Aircraft*, *47*(1), 303-314. DOI: 10.2514/1.45452
6. Bilgen, O., & Friswell, M. (2013). Piezoceramic composite actuators for a solid-state variable-camber wing. *Journal Of Intelligent Material Systems And Structures*, *25*(7), 806-817. DOI: 10.1177/1045389x13500575
7. Current Market Outlook. (2013). Retrieved 23 March 2022, from http://787updates.newairplane.com/Boeing787Updates/media/Boeing787Updates/Aviation%20Experts/Boeing_Current_Market_Outlook_2013.pdf
8. Elzey, D., Sofla, A., & Wadley, H. (2003). A bio-inspired high-authority actuator for shape morphing structures. *Smart Structures And Materials 2003: Active Materials: Behavior And Mechanics*. doi: 10.1117/12.484745
9. Galantai, V., Sofla, A., Meguid, S., Tan, K., & Yeo, W. (2011). Bio-inspired wing morphing for unmanned aerial vehicles using intelligent materials. *International Journal Of Mechanics And Materials In Design*, *8*(1), 71-79. DOI: 10.1007/s10999-011-9176-0
10. Henry, A., Molinari, G., Rivas-Padilla, J., & Arrieta, A. (2019). Smart Morphing Wing: Optimization of Distributed Piezoelectric Actuation. *AIAA Journal*, *57*(6), 2384-2393. DOI: 10.2514/1.j057254
11. Huang, X., Kumar, K., Jawed, M., Mohammadi Nasab, A., Ye, Z., Shan, W., & Majidi, C. (2019). Highly Dynamic Shape Memory Alloy Actuator for Fast Moving Soft Robots. *Advanced Materials Technologies*, *4*(4), 1800540. DOI: 10.1002/admt.201800540
12. Lagoudas, D., Miller, D., Rong, L., & Kumar, P. (2009). Thermomechanical fatigue of shape memory alloys. *Smart Materials And Structures*, *18*(8), 085021. DOI: 10.1088/0964-1726/18/8/085021

13. Lyu, Z., & Martins, J. (2014). Aerodynamic Design Optimization Studies of a Blended-Wing-Body Aircraft. *Journal Of Aircraft*, *51*(5), 1604-1617. DOI: 10.2514/1.c032491
14. Mader, C., & Martins, J. (2013). Stability-Constrained Aerodynamic Shape Optimization of Flying Wings. *Journal Of Aircraft*, *50*(5), 1431-1449. DOI: 10.2514/1.c031956
15. Mammano, G., & Dragoni, E. (2012). Functional fatigue of NiTi Shape Memory wires for a range of end loadings and constraints. *Frattura Ed Integrità Strutturale*, *7*(23), 14-33. DOI: 10.3221/igf-is.23.03
16. Markvicka, E., Bartlett, M., Huang, X., & Majidi, C. (2018). An autonomously electrically self-healing liquid metal–elastomer composite for robust soft-matter robotics and electronics. *Nature Materials*, *17*(7), 618-624. DOI: 10.1038/s41563-018-0084-7
17. Merino-Martinez, R. (2022). Retrieved 23 March 2022, from https://www.researchgate.net/publication/263234250_Design_and_Analysis_of_the_Control_and_Stability_of_a_Blended_Wing_Body_Aircraft
18. P, N., Arokkiaswamy, D., & Alen A, A. (2019). Shape Optimization of Blended-Wing-Body Configuration- An Experimental Approach. *SSRN Electronic Journal*. DOI: 10.2139/ssrn.3507300
19. Schlup, A., Bishay, P., Mclennan, T., Barajas, C., Talebian, B., & Thatcher, G. et al. (2021). MataMorph 2: A new experimental UAV with twist-morphing wings and camber-morphing tail stabilizers. *AIAA Journal*, (2021-0584). DOI: https://doi.org/10.2514/6.2021-0584\
20. Sun, J., Guan, Q., Liu, Y., & Leng, J. (2016). Morphing aircraft based on smart materials and structures: A state-of-the-art review. *Journal Of Intelligent Material Systems And Structures*, *27*(17), 2289-2312. DOI: 10.1177/1045389x16629569