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Review

# Application of Shape Memory Alloy Actuators to Vibration and Motion Control of Structural Systems: A Review

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**Abstract:** This paper comprehensively reviews effective control applications using shape memory alloy (SMA) actuators. Among many applications, this paper focuses on the vibration and stiffness control of flexible structures and shape control in the aerospace engineering field. In the vibration control of flexible structures, three different methods are introduced and discussed, including their merits and demerits. In addition, several control strategies, such as neuro-fuzzy controller, are investigated in terms of the implementation associated with the microchip. In the control process, the inherent hysteretic behavior of SMA is also reviewed as a feedforward loop or actuating force compensator. At the second part, applications on the morphing wing in the field of aerospace engineering are reviewed, and salient characteristics are discussed. In this review, the morphing wing, which is closely related to aircraft stability, is mainly investigated considering control logics and geometrical parameters. For easily understanding morphing control using SMA, a table which summarizes the main contribution of each research is presented. It is expected, since this review article provides numerous approaches for vibration and morphing control conducted over the last decade, it will be very helpful to the same research community to create novel ideas to achieve more advanced and effective results in vibration and morphing control using SMA actuators.

**Keywords:** shape memory alloy; actuator; vibration control; flexible structure



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## 1. Introduction

From the late 1980s and early 1990s, research on the applications of various smart materials has exploded, and these studies have been continuously reported to this day. Engineering application research on various smart materials, such as piezoelectric materials, magnetorheological/electrorheological fluids, and electroactive polymers, is actively being presented, and among these various smart materials, shape memory alloys (SMA) are a material receiving constant attention. Since SMA memorizes its shape in a high temperature state, it has the property of being deformed in a low temperature state and then restored to its shape in a high temperature state when the temperature is raised by applying heat. In 1932, the solid deformation of SMA was first discovered by observing that gold–cadmium alloy was plastically deformed at low temperature and can be returned to its original shape when heated [1]. The commercialization of SMA became possible only after William Buehler and Frederick Wang discovered Nitinol in 1962, which has low production cost, safety, and excellent mechanical performance compared to existing products [2,3]. SMA has the disadvantage of a slow reaction rate because the temperature must be changed by external heat, but it has the advantage of being small in volume, biocompatible, and having high actuation force. In addition, it has the advantage that it can be manufactured in various forms such as wire, spring, and strap. Taking advantage of these points, SMA is being studied for application in various engineering fields.

Various review papers on SMA have been reported in the material-level point of view and modeling/simulation point of view, and, among them, some papers on the actuator application point of view are also reported. Jani et al. presented a review on the progress and development in optimization of an SMA linear actuator with different design methods, techniques, and approaches [4]. Yuan et al. reviewed rotary actuators triggered by SMA and discussed the characteristics and possibilities of SMA actuators for engineering applications [5]. Hu et al. provided a review of research works related to SMA actuators for bi-directional rotational motion [6]. To obtain shape changing, investigations on design methods for the origami robot applications were conducted. Dana et al. reported a review article on various aspects of high-speed actuation of SMA wires in the high driving force regime. [7]. Zhang et al. summarized the development and application of Fe-SMA technology in civil engineering, covering various aspects such as structural retrofitting and seismic damping. [8]. Ruth et al. reviewed SMA actuators in robotic applications over the last decade focusing on the control aspects of the actuator [9]. Suman et al. reported in a review paper for SMA actuators for morphing wing application, and they focused on the design strategies of actuators [10]. As described above, although various review papers about SMA actuators have been published, a review article focusing only on the vibration and morphing motion control of structural systems using SMA actuators is considerably rare.

Consequently, the main contribution of this review paper is to focus on the application of SMA actuators to the field of structural control systems, including both vibration and stiffness control of flexible structures and shape control in aerospace engineering. An in-depth review of papers published over the last decade was conducted to investigate the system characteristics and control results of research in the related fields. In this review, structural vibration control and wing morphing control were selected as major research items since they are easily integrated with SMA actuators: wire, film, embedded composite, and so forth. It is remarked that various research works are summarized using tables to clearly show the effectiveness, implemented controller, and possible applications. These tables can provide the guideline for the choice of SMA types and geometrical parameters of the structural mechanisms. Magnetic shape memory alloys capable of generating force or motion by applying a magnetic field were introduced in 1996, and various studies have been conducted until recently. Generally, magnetic shape memory alloy is an alloy of nickel, manganese, and gallium (Ni-Mn-Ga). However, magnetic shape memory alloys are different from thermal shape memory alloys in their driving method and are not yet actively applied in the aerospace field, so they are not included in the research scope of this review paper. In addition, various modeling techniques have been proposed to compensate for the hysteresis characteristics of shape memory alloys, and control algorithms have been proposed based on these models. However, this review paper focused on application fields and control algorithms, and modeling techniques were not included in the scope of this review paper.

## 2. Application to Flexible Structures

The concept on the active vibration control of flexible beams using an SMA actuator was initiated in the 1990s [11,12]. In these articles, simple control strategies such as constant amplitude controller and proportional amplitude controller have been implemented to reduce transient vibrations by operating an SMA actuator installed at the outside of the beam. This type of system architecture was reported until the mid-2000s [13,14]. Thereafter, vibration control of flexible structures has been working in three different ways as shown in Figure 1. As shown in Figure 1a, controlling the vibration of a structure by attaching a wire or spring type SMA actuator to the outside of the structure is the most proposed configuration. It has the advantage of simple system configuration and intuitive control, but also has the disadvantage that the actuator can be affected or damaged by the external environment. As shown in Figure 1b, another configuration is to insert SMA wires or springs into the structure to form a composite material. Although there is an advantage in that the SMA actuator can be protected from the external environment, there is a disadvantage in that the difficulty of manufacturing the system is high. Although not common, it is possible to attach an SMA actuator in the form of a film or strip to the surface of a structure, as shown in Figure 1c.

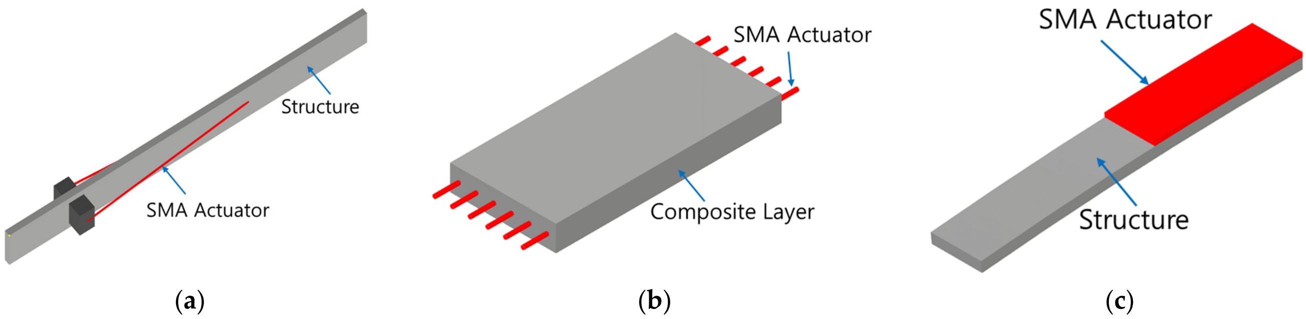



**Figure 1.** The schematic location of SMA actuator for vibration control of flexible structures. (**a**) Beam external; (**b**) Plate/Composite embedded; (**c**) Film bonded to the surface.

*2.1. Structural Vibration Control*

Studies on the application of SMA actuators for vibration control of various flexible structures with beams and plates have been continuously reported. Suzuki and Kagawa designed the H-inf controller based on the state space model governing the motion of SMA-beam structure and experimentally implemented the controller to effectively reduce unwanted vibrations in both transient and forced vibration cases [15]. Dhanalakshmi et al. implemented several control algorithms associated with an SMA actuator to control unwanted vibrations of a flexible beam [16]. They formulated the online recursive square parameter estimator based on the auto-regressive model and evaluated control efficiency of an on–off controller; proportional and integral (PI) controller; and proportional, integral, and derivative (PID) controller. Wierschem and Andrawes proposed a passive control method by developing a composite structure reinforced with super-elastic shape memory wires and showed the increment of the tensile strength by activating SMA wires [17]. Hadi et al. carried out both vibration and position control of a flexible structure using two SMA springs that are integrated with the variable structure controller and the pulse width modulation method [18]. Scirè Mammano and Dragoni introduced an elastic compensation system to resolve drawbacks of the SMA actuator: short stroke and inhomogeneity of useful force over the stroke in which a rocker-arm compensating mechanism was used as a proof-of-concept actuator [19]. Saito et al. proposed a new method of operator-based nonlinear vibration control of a flexible arm using an SMA actuator in which the input is determined Lipschitz condition and robust right coprime factorization condition based on the Prandtl–Ishlinskii hysteresis model [20]. The configuration of the vibration control system of a representative flexible beam structure is shown in Figure 2.

Damanpack et al. presented the passive vibration control capability of SMA composite beams subjected to various blast pulses where the influence of temperature, place, pre-strain, and thickness of SMA layers have been investigated through the transient response in time domain [21]. Holanda et al. proposed an SMA actuator with a helical coil spring shape for the vibration control of a single-degree-of-freedom system subjected to unbalanced excitement force in which the control of complex stiffness to reduce the resonance vibration has been emphasized [22]. Zakerzadeh and Sayyaadi implemented a hybrid controller consisting of the inverse of the generalized Prandtl–Ishlinskii hysteresis model and PI controller for accurate deflection control by decreasing the steady state error of a large deformation structure [23]. Chenal et al. developed a variable stiffness fabric using

SMA covered with a shape memory polymer (SMP)-based thin film and its mechanical property showing the force versus deflection was investigated at different temperatures [24]. Kim et al. manufactured an SMA beam by heat treatment after spray deposition to achieve high damping capacity quantified based on the concept of Hilbert transform [25]. Wang and Mak investigated the vibration control problem with broadband and nonrigid systems retaining periodic structures using a semi-two-dimensional model associated with SMA branches and non-SMA dual beams in which unwanted vibrations were attenuated in a broadband frequency by applying proper temperatures to SMA branches [26]. Ma et al. proposed an active device for vibration control of the rotor dynamic system using SMA metal rubber where vibration amplitude was evaluated as a function of the critical speed [27].

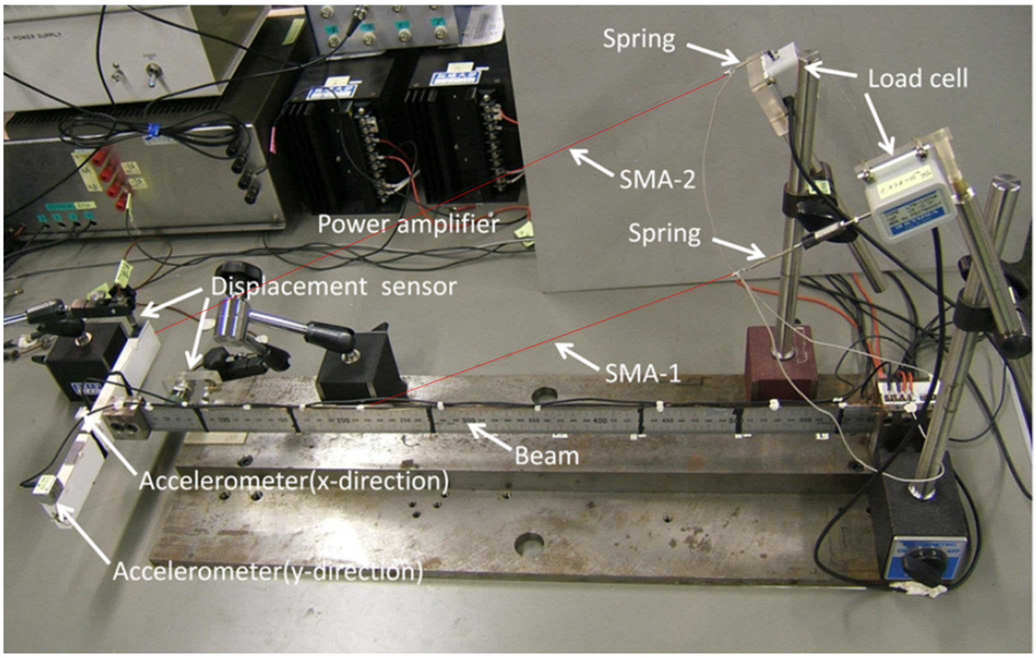



**Figure 2.** Vibration control of flexible beam structure. 

Suzuki proposed the pair of antagonistic SMA wires for vibration control of a flexible cantilever beam subjected to air flow (external excitation) from the wind tunnel in which the control voltage to be applied to SMA actuator was determined from a gain-scheduled H-infinity controller taking account for ambient airflow conditions [28]. Mekaouche et al. developed the compliance map variability of a flexible link structure using SMA springs and adopted the concept of driving a virtual workspace from structural deformation with a small and large displacement hypothesis [29]. Santos and Cismaşiu proposed an adaptive-passive beam with SMA actuator based on an underslung cable-stayed girder concept in which the temperature modulation was achieved from a closed-loop control associated with the PID controller [30]. Shen et al. used a restoring force generated from SMA wire to realize vibration control of flexible structure in which the resonance due to external disturbance was avoided by changing the natural frequency of the beam structure to be increased or decreased depending on the restoring force of SMA wire [31]. Sousa et al. investigated the aeroelastic behaviors by implementing the passive pseudo-elastic hysteresis of SMA springs in which the range of post-flutter airflow speeds with stable limit cycle oscillation was analyzed by activating SMA springs with the synchronized switching damping technique [32]. Alipour et al. proposed a tension-compression self-centering damper based on the energy dissipation of pre-stretched SMA wire. One of these damping groups was activated during tension and the other during compression to increase the damping capacity of the system [33]. Santos and Nunes proposed an adaptive vibration absorber for vibration control of civil structures using the real-time temperature modulation of SMA through Joule effect, which could control the elastic modulus of the structures and hence achieve a wide range of tuning the frequency for stiffness adaptation [34].

Vishal et al. presented an active vibration control system for the cantilever beam using SMA wires where a nonlinear controller based on the dynamic inversion and optimal control was realized after optimally installing the actuators and sensors [35]. Lin et al. developed a tunable vibration absorber using SMA and applied it to suppress the vibrations of a planar structure using the interval type-2 fuzzy controller describing the nonlinear mapping between the input and the output [36]. Das et al. presented SMA-based stiffening strategy to reduce blade vibration of the large horizontal axis wind turbine where the aerodynamic loads acting on the blades were evaluated via the blade element momentum theory [37]. Joseph and Podder applied SMA wire to a flexible needle to achieve precise tracking in medical interventional procedures where an adaptive sliding mode controller was implemented to keep the robustness against uncertainties [38]. Garafolo and McHugh have embedded SMA wire into a silicone beam to achieve different natural frequencies and vibration modes of the beam structure in which the avoidance of the resonance behavior due to external excitation can be effectively achieved by activating SMA wire with different temperatures [39]. Zhang et al. devised a new hydraulic SMA shock absorber that uses an SMA bar as the core of a component for energy dissipation and recovery in the stress mode of pure tension and whose initial deformation is enlarged by a hydraulic system with two sizes of pistons [40]. Alves et al. investigated the influence of SMA on the dynamic behaviors of flexible rotors in which a suspension composed by SMA wires was connected to the rotor-bearing test rig to achieve stiffness tuning due to the hysteretic cycle denoting energy dissipation [41]. Ameduri et al. devised an adaptive system focusing on the enhancement of the soundproof performance of car door seals using SMA wires, which was integrated within the seal cavity to reduce the sound [42].

Ying and Minglei investigated the nonlinear random vibration of axially moving SMA composite beam subjected to transverse loads as a function of the axial movement velocity. Using the stochastic averaging method, the amplitude frequency response equation under primary resonance and the probability density function under random perturbation were derived [43]. Ghasemi et al. applied the optimized SMA damper to control wave-induced vibrations of fixed jacket platforms where the ideal gas molecule movements method was implemented to minimize the deck displacements under the action of an extreme wave [44]. Tan et al. proposed a single-sided pounding tuned mass damper using SMA sponge to mitigate the transient and force vibrations of a suspended piping system in which the SMA damper was utilized as a passive damper possessing high energy dissipation characteristics [45]. Utter investigated the feasibility of a new approach to obtain more rapid cooling of SMA wires. It was because a steel spring pin placed on the wire induces a first vibration mode driven by an electromagnet when the SMA is cooled [46]. Wang et al. investigated vibration control of a fixed–fixed beam using a piezo-SMA ferrule. The stability of the proposed beam structure could be improved by a self-regulation of the stiffness of the proposed actuator subjected to external excitations [47]. Park et al. proposed a unique sound absorber to tune the geometry manipulation using the reversible shape-changing ability of an SMP foam in which the micro-structure of foam was recovered to control the sound absorption capability dependent on frequency [48]. Liu et al. applied SMA cables to the girder bridges in order to reduce unwanted vibration and hence increase traffic safety and comfort where both the bending and torsional vibrations were analyzed by the finite element method [49]. Ali et al. investigated the mechanism of load transfer at the interface of SMA and glass fiber-reinforced plastic (GFRP) to detect the crack problem, which can reduce the stiffness of the hybrid composites. The pull-out test was undertaken with the hybrid composite specimens under plain SMA insert exhibiting the micro-cuts [50].

Keshtkar et al. designed a penalty-based sliding mode control law to actively control the flexible bar using an SMA actuator in which control force manipulates SMA to exert the necessary force for deflecting the flexible bar into the desired state [51]. Zardian et al. proposed a composite beam reinforced with SMA wires for free vibration control where both the static and dynamic behaviors of the beam with different volumetric fiber fractions were evaluated by analyzing the change of natural frequencies due to heat activation [52]. Alambeigi et al. investigated the free and forced vibration behaviors of a sandwich beam with functionally graded porous core and composite face layers embedded with SMA in which the change of the natural frequencies of the beam was evaluated as a function of the temperature, and vibration amplitude was shown at different external forces [53]. Cao et al. proposed a multi-level SMA/lead rubber bearing isolation system to ensure both isolation efficiency and displacement attenuation under different levels of earthquake excitations in which a four-span continuous box-girder bridge system was designed and analyzed in terms of nonlinear dynamics [54]. Lu et al. proposed SMA-based friction damper consisting of the friction plate and SMA cable for vibration control of civil structures such as bridges where the effects of the loading frequency, displacement amplitude, and number of SMA wires on the hysteretic behavior of the friction damper were investigated using three different structures [55]. Patterson et al. investigated an SMA slat-cove filler to reduce noise for the leading-edge-slat high-lift system where aero-structural experiments were conducted incorporating with the digital image correlation measurements and measured displacement from the laser sensor [56]. Vignoli et al. investigated the use of SMA composites in a one-story frame structure subjected to earthquakes in which both linear matrix and elastoplastic matrix with isotropic and kinematic hardening were considered [57]. Mao et al. assessed the concrete bridge piers subjected to the seismic loadings with different reinforcement alternatives associated with SMA where the seismic responses were evaluated by the maximum drift, residual drift, and energy dissipation [58]. Akbari et al. investigated the bending deformation of a flexible structure using SMA wire and SMP layer in which the SMA–SMP composite actuators were fabricated using 3D printing, and the stiffness modulation for shape retention and recovery was achieved from embedded SMP segments of different thickness whose temperature could be controlled through Joule heating [59]. Das et al. proposed an SMA-based inerter combined with electromagnetic transducer for vibration control of buildings where both the equivalent linearization for efficient input–output characterization and the ensemble surrogate analysis for the stochastic response quantification were used to validate the efficiency of vibration control capacity of a high story building as a function of wind speed [60]. Srivastava and Bhattacharya proposed a hybrid structure consisting of SMA and E-glass fiber reinforced composite to investigate the change of the stiffness and hence the natural frequencies from the free vibration response where both the fiber volume and fiber orientation were chosen as design parameters [61].

Various studies using SMA actuators have been proposed to control the vibration of single-link or two-link flexible arm structures. Janzen et al. implemented an optimal control of linear quadratic regulator (LQR) for vibration control of a single-link flexible arm during the rotational motion by direct current (DC) servo motor [62]. Quintanar-Guzmán et al. presented design and control of two-link flexible robot arm using SMA wires to achieve precise position tracking of the end-effector in which four different controllers of proportional and derivative (PD) controller, sliding mode controller, adaptive control law, and adaptive sliding mode controller were realized, and their control performances were compared [63]. Matsumori et al. presented an operator-based control system to control unwanted vibration of a flexible arm using SMA actuator in which the hysteresis and thermal compensator was considered to overcome the temperature change around the SMA actuator for long-term use of the system [64]. Research works using SMA actuators have been also proposed to control the vibration of flexible structures other than beams or plates. Li et al. proposed a non-contact and temperature-independent technique to suppress the vibration of rings using a light-activated SMP where the phase shift and neural network controller were implemented to enhance the actuating efficiency of SMP and hence vibration reduction capacity [65]. Lu et al. proposed a thin-walled cylindrical shell with SMA driven screw-type actuators to actively control the stiffness and hence natural frequencies where the geometric parameters of the actuators were optimized based on the static and model analysis of the system, and the influence of the actuator number and actuation time on the control performance was investigated [66].

Table 1 presents a summary of vibration control methods of flexible structures using an SMA actuator. As noticed from the table, many active controllers such as sliding mode controller and fuzzy controller have been implemented in the period of 2010-2018, but there are several works on passive control methods in 2020 and 2021. This change of control strategy is closely related to real applications in practical environments where reliability of the control system and cost effectiveness are critical issues to be seriously considered.

**Table 1.** Control methods for flexible structures.

| Reference | Control Type | Controller | Application |
|---|---|---|---|
| [15] | Robust Control | H∞ controller based on the state space model | vibration control of a flexible beam |
| [28] | | gain-scheduled H∞ controller | vibration control of a cantilever beam |
| [38] | | adaptive sliding mode controller | vibration control of a flexible needle |
| [51] | | penalty-based sliding mode control law | vibration control of a flexible bar |
| [63] | | adaptive sliding mode controller | vibration control of a two-link arm |
| [62] | Optimal Control | LQR controller | vibration control of a one-link arm |
| [16] | PID Control | PI and PID controller | vibration control of a flexible beam |
| [23] | | hybrid control with PI controller | control of large tip deflection |
| [30] | | PID controller | vibration control of an adaptive-passive beam |
| [18] | Others | hybrid control based on variable structure controller | position and stiffness control of a flexible plate |
| [20] | | operator-based controller with hysteresis compensator | vibration control of a flexible beam |
| [36] | | interval type-2 fuzzy controller | vibration control of a planar structure |
| [64] | | operator-based controller | vibration control of a flexible arm |
| [65] | | phase shift and neural network controller | vibration control of rings |
| [66] | | screw-type active controller | natural frequency control of a cylindrical shell |
| [43] | Passive | passive control (stochastic averaging method) | axial vibration control of composite beam |
| [47] | | passive control (self-regulation of the stiffness) | vibration control of fixed-fixed beam |

## 2.2. Other Structural Applications

Tai and Ahn designed a direct adaptive controller and applied it to an SMA actuator to reduce the measurement noise and estimate the system states by compensating the hysteresis behavior [67]. Ayvali and Desai presented a temperature feedback approach to control the radius of arc-shaped SMA wire using the pulse width modulation (PWM) method. The PWM-based nonlinear PID controller featuring a feedforward heat transfer model was realized to track the desired temperature trajectory [68]. Guo et al. devised two antagonistic SMA wires and a mechanical joint coupled with a torsional spring to higher performance compared with the bias SMA actuator in which the differential SMA wire was used to increase the response speed, while the torsional spring was used to reduce the total stiffness of the SMA actuator itself [69]. Faroughi proposed an adaptive absorber using an SMA actuator for vibration control of the spring-mass system in a wide range of frequencies where passive control method associated with the phase transformation was implemented [70]. Nalini et al. devised a linear actuator using synergistically configured SMA wires to achieve variable stiffness actuation in which both the stiffness feedback controller and force feedback controller were implemented [71]. Gurley et al. utilized advantages of the Bowden tube, which can provide faster actuation speed by devising Bowden tube SMA actuators consisting of a rotary platform and a micro controller in which a sliding mode controller was realized to take account for uncertain parameters [72]. Berardengo et al. proposed an adaptive multi-modal tuned mass damper using SMA wires to change the eigenvalues of the structure and hence recover shifts of the natural frequencies in which one SMA wire was used to change of the axial load and the other wire to change the geometry of the device [73]. Braga et al. used SMA wires to achieve passive control of mechanical vibrations of rotating machines where the amplitude of the lateral vibrations of a rotating shaft was reduced by thermally activating SMA wires [74]. Vibro-acoustic radiation of a laminated composite structure, which has SMA orthogonal asymmetry, was proposed by Huang et al. [75]. The governing equations were derived by using the constitutive equation, Hamilton principle, and energy methods. It was demonstrated that the composite laminates embedded with SMA wires have good performance to adjust the mode frequency and can change sound radiation characteristics.

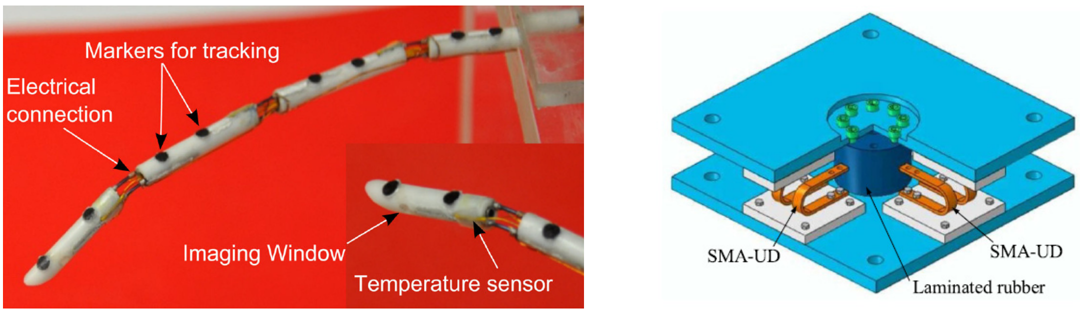
Several studies have been presented for the use of SMA actuators in systems to prepare for earthquakes in civil engineering. Qian et al. developed a passive SMA damper for structural seismic protection where the SMA damper has been installed on the building structure as an energy dissipative device associated with the hysteretic behavior [76]. Azimi used a fuzzy logic controller to control unwanted vibrations of civil structures using an SMA actuator in which the maximum roof displacement of a five-story building structure was evaluated [77]. Cao and Ozbulut proposed a long-stroke SMA restrainer consisting of an SMA bar, a steel tube, and a filler material to achieve both energy dissipation and restrainer under cyclic tension and compression loadings in which bucking and post-bucking response of the SMA bar were characterized via finite element analysis [78]. Tiwari et al. devised a passive control device for vibration using an SMA tuned mass damper inerter. Here, the SMA element and the mass amplification effect of the inerter was used to dissipate the energy of the primary oscillator through hysteretic phase conversion and utilized to reduce the oscillation displacement of the secondary oscillator, respectively. [79]. Wang et al. devised the deformation mechanism of super-elastic SMA U-shaped dampers for vibration control of civil structures subjected to seismic excitation in which the stable energy dissipation under the different direction of the loadings was analyzed via the finite element method [80]. The applications and control methods for various structures are summarized in Table 2. It is clearly seen that the passive controller is used in many applications. Examples of the application of the radius of curvature control and vibration control of civil structures using SMA actuators are shown in Figure 3a,b, respectively.

**Table 2.** Control methods for various structural systems.

| Reference | Control Type | Controller | Application |
|---|---|---|---|
| [72] | Robust Control | sliding mode controller | fast control of a rotary platform |
| [67] | Adaptive Control | direct adaptive controller | position control |

**Table 2.** *Cont.*

| Reference | Control Type | Controller | Application |
|---|---|---|---|
| [68] | PID Control | PWM-based nonlinear PID controller | control the radius of curvature |
| [69] | | PI controller | position control using compliant differential |
| [77] | Others | fuzzy logic controller | vibration control of civil structures |
| [71] | | stiffness and force feedback controller | stiffness control |
| [70] | Passive | passive controller with phase transformation | adaptive absorber for spring-mass system |
| [73] | | passive controller (multi-modal tuned mass damper) | control of natural frequency |
| [74] | | passive controller (thermal control method) | vibration control of rotating machines |
| [75] | | passive controller | sound radiation control |
| [76] | | passive controller | seismic vibration control of structure |
| [54] | | passive controller (multi-level SMA/lead rubber bearing isolation) | earthquake control |
| [79] | | passive controller (tuned mass damper inerter) | vibration control of oscillator |
| [80] | | passive controller (super-elastic SMA U-shaped damper) | vibration control of civil structures |




(**a**) (**b**)

**Figure 3.** Control of various applications: (**a**) radius of curvature control for steerable cannula [68] Reproduced with permission from SAGE under STM Permissions Guidelines; (**b**) vibration control of civil structures subjected to seismic excitation [80] 

## 3. Aerospace Engineering Applications

After the first application of SMA to the hydraulic tubing coupling on the F-14 fighter in 1971, aerospace engineering has long been one of the major fields of research for the use of SMA actuators. From the 1990s to the early 2000s, many SMA-based research programs were carried out such as the "Smart Wing Project" and the "Smart Aircraft and Marine Propulsion System Demonstration (SAMPSON) Program" for jet engine by DARPA, NASA, and Boeing, Hartl and Lagoudas [81]. As presented in Figure 4, the potential applications of an SMA actuator in aerospace engineering are for structural morphing, engine, landing gear release mechanism, and so on. In this section, the aerospace engineering applications of an SMA actuator in the last decade are described and summarized.

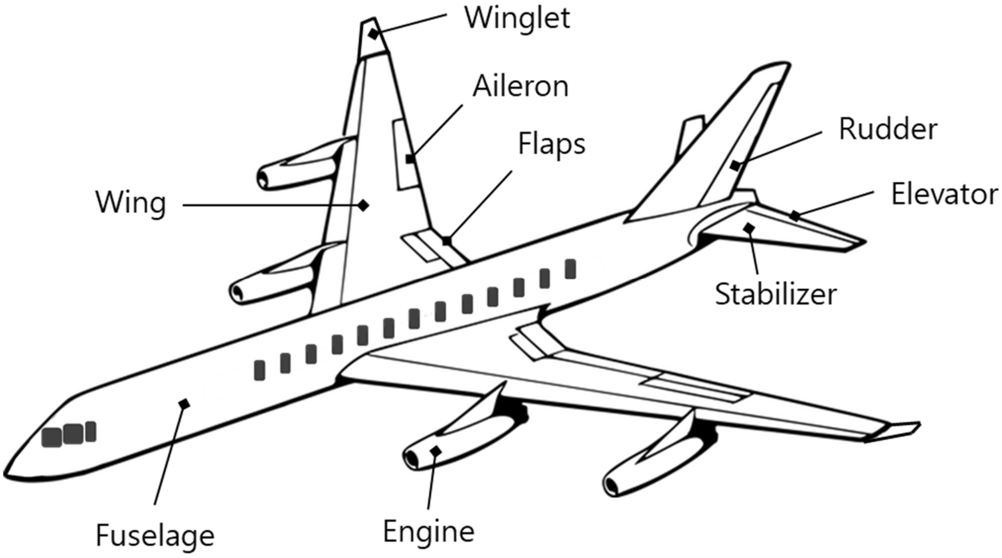



**Figure 4.** Applications of SMA in airplane.

### *3.1. Aplication to Wing Morphing*

One area with great potential to significantly improve aircraft performance is the structural morphing of the aircraft, especially the shape morphing wing. The classifications of the shape morphing wing are presented in Figure 5.

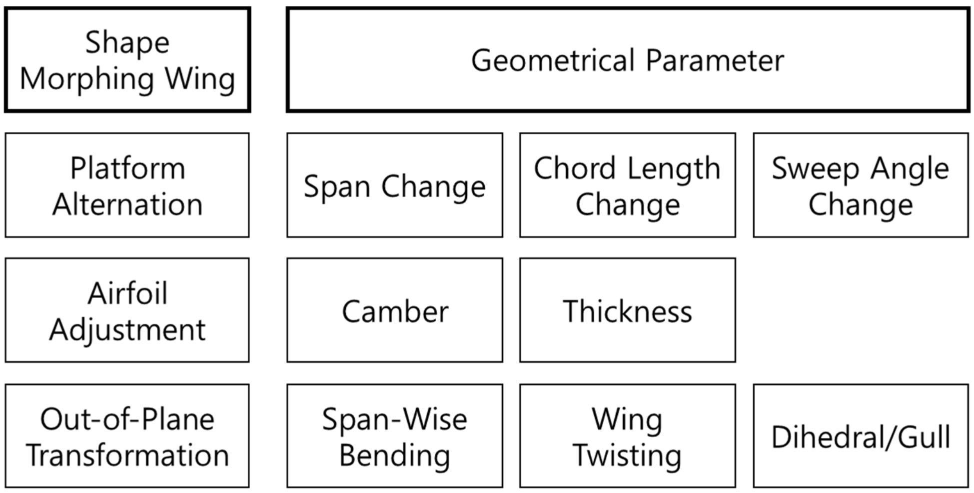



**Figure 5.** Classification for shape morphing wing and its geometrical parameters.

Barbarino et al. designed a reference shape based on a full-scale wing of a regional transport aircraft and proposed a flap architecture for a variable camber trailing edge [82]. The compliance rib is based on a truss structure in which some members are SMA-based active rods. The structural performance was estimated using FE analysis. Brailovski et al. proposed a group of SMA actuators [83]. The proposed actuator includes a flexible extrados, a transmission system including the slider and the crank, a compression bias spring, and an SMA active element. The performance of the proposed actuator system was evaluated via wind tunnel test. Calkins and Mabe reported a review paper about SMA-based morphing aero-structures developed in the past decade [84]. The review paper reported on five large-scale SMA-based technology programs initiated by the Boeing Company: deployable rotor blade aerodynamics, variable geometry chevrons, smart inlets, reconfigurable rotor blades, and variable area fan nozzles. For the morphing of the laminar wing, Coutu et al. numerically investigated the optimal design of an active extrados structure [85]. They identified two key design parameters. The first is the number of plies in the flexible extrados composite laminate and the second is the number of actuators. To achieve a balance for the compromise between rigidity and flexibility of the active extrados structure, aerodynamic and mechanical performance criteria were considered simultaneously. The proposed conceptual design of the morphing laminar wing is presented in Figure 6. Popov et al. presented the modeling and testing of an SMA actuator-based morphing wing in open-loop control architecture [86]. The proposed flexible skin was designed to deform the shape of the airfoil through deformation of two operating points in order to create an airfoil shape optimized for the theoretical fluid flow conditions. The SMA actuator was activated by a power supply unit and controlled using the self-tuning fuzzy controller. Popov et al. also presented closed-loop control configuration and the displacements of the SMA actuator were automatically determined as a function of the pressure obtained from the wing top surface [87]. Sofla et al. proposed two morphing wings that can be deformed to a specific target shape using an SMA actuator [88]. In the first design, the straight wing is slid and deformed into a curved shape, and, in the second design, the wing is bent in the lateral direction. The prototypes exhibited good and smooth movement under the applied loads. To evaluate the effect of the morphing wing on the lift and drag coefficients, the parametric aerodynamic analysis was carried out. One area with great potential to significantly improve aircraft performance is the structural morphing of aircraft, especially the shape morphing wing.

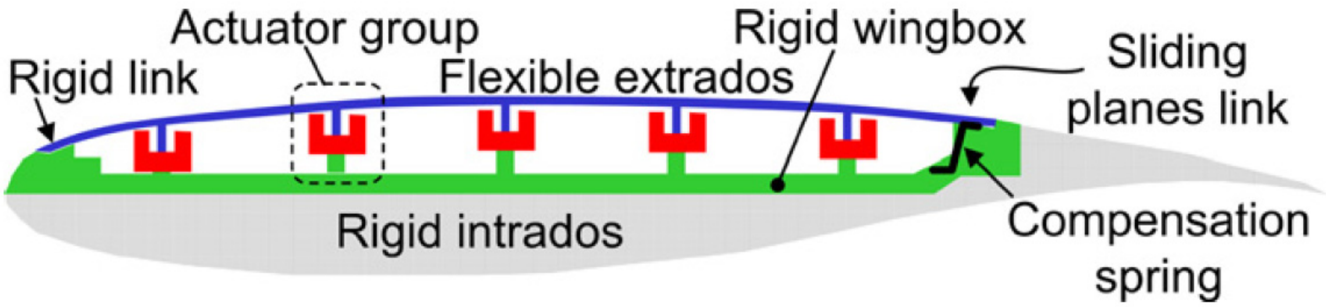



**Figure 6.** Conceptual design of the morphing laminar wing [85] Reproduced with permission from Elsevier under STM Permissions Guidelines.

Grigorie et al. developed a controller by combining on–off, bi-positional, and PI controllers for an actuation control of a morphing actuation mechanism by considering two heating and cooling phases of the interconnected SMA wire actuators [89]. The proposed controller acts as a switch between the cooling and heating stages in the case of an output current of 0 A. The control inputs by the PI controller in the heating stage were optimally determined using integral and surface minimum error criteria. Grigorie et al. also reported the numerical simulation and experimental validation results for the control system in a morphing wing application [90]. Grigorie et al. designed a hybrid fuzzy-PID controller and demonstrated its control performance under subsonic wind tunnel conditions [91,92]. For a flapping wing, a novel morphing wing mechanism was proposed by Kang et al., and an SMA actuator was used to achieve a smooth change of the wing configuration to prevent aerodynamic losses [93]. After fabricating a prototype wing to demonstrate the morphing mechanism, the deflection angles at the trailing edge were evaluated according to various input currents. Senthilkumar used SMA actuators to deflect the plain flap and control the flap angle of the aircraft wing [94]. He fabricated SMA-controlled aerofoil structures with flap and experimental investigation under wind tunnel conditions. In this work, he used a switching circuit to control the two sets of SMA wire actuators alternatively. Song and Ma proposed an adaptive exhaust nozzle for jet engines featuring SMA actuators [95]. The open area of the exhaust nozzle was actively controlled by an SMA actuator.

Bil et al. reported control performance evaluation of a morphing wing with SMA actuators for small-sized and medium-sized unmanned air vehicles [96]. In this work, the camber line of an airfoil section was controlled by using resistive heating and cooling in the surrounding air of the SMA actuator. To investigate the effects of the proposed morphing wing concept, experiments were conducted under wind tunnel condition with three control methodologies: the conventional PID controller, PID controller with anti-windup compensator, and PID controller with robust compensator. Wang et al. proposed morphing trailing edge design with SMA to achieve controllable deflection motion under the aerodynamic load [97]. After manufacturing a prototype of the trailing edge with four sections of aluminum alloy, deflection angle test was conducted, and precise control of the morphing wing was realized. Barbarino et al. also reported in a review paper SMA applications to morphing aircraft. They emphasized variable twist of camber, reduction of power consumption, and actuation bandwidth [98]. Jani et al. reported in an in-depth review paper about SMA applications, and they clearly summarized various studies in the aerospace field conducted up to that time [99]. They classified the parts where SMA was or was likely to be applied in aerospace engineering and summarized the research literature at the time for each part. Karagiannis et al. investigated the flapping system based on the SMA thin wires [100]. The camber of trailing edge in a civil regional transportation aircraft was morphed by using an SMA actuator. The numerical and experimental results showed that the SMA actuation mechanism can perform its role adequately in loads providing morphing conditions. Ko et al. proposed, designed, and fabricated an SMA spring actuators-based morphing flap, and analytical and experimental investigation on its aerodynamic characteristics were conducted [101]. Two types of morphing flaps were proposed, and they were composed of three-element and six-element configurations. The proposed conceptual design for morphing airfoil is presented in Figure 7. Rodrigue et al. introduced a new design for a soft morphing actuation of pure twisting motion by using SMA wires [102]. The proposed actuator system consists of a pair of SMA wire actuators that were embedded in a polymer matrix at constant and opposite eccentricity across the cross section in opposite directions. It was demonstrated that there was an optimal actuator thickness for both the twisting angle and the twisting force of the actuator. In addition, for the thickness of the actuator, there was a trade-off between the twisting angle and force.

The aerodynamic performances of a morphing winglet for an unmanned aerial vehicle (UAV) were investigated by Han [103]. The morphing winglet was designed by mimicking gliding birds' wing tip. The morphing winglet was fabricated by using a smart soft composite, which consists of glass fibers and SMA wires within a polymer matrix. After manufacturing a prototype of morphing winglets, the aerodynamic performances were evaluated under the wind tunnel test under various attack angles. It was confirmed that aerodynamic performance of the UAV can be improved by controlling the wing-tip configuration with consideration of the inclined angle of the UAV. The proposed morphing winglet for UAV is presented in Figure 8. Sun et al. reported on research works on morphing wings using SMA actuators in a review paper on morphing aircraft using smart materials [104]. In addition to the morphing structure technology using the SMA actuator, various morphing structure technologies using piezoelectric materials, electro-active polymers, and magnetostriction were summarized and reported. Bashir et al. reported in an introspective paper about SMA applications in aircraft morphing technology [105]. They compared the characteristics of SMA, SMP, and shape memory polymer composites (SMPC), and the aerospace applications of each material are summarized. Hattalli and Sritvasa investigated a case study of camber change for the horizontal tail in the UAV, and a numerical simulation was conducted to exam the SMA actuator-based camber change [106]. A maximum deflection of 0.6 mm at the trailing edge tip was detected in the numerical results. Sellitto and Riccio reported in a review paper about morphing surfaces using SMA actuators [107]. After giving an overview of research on SMA actuators, adaptive aerodynamics applications of an SMA actuator were investigated. The numerical case study was investigated for the feasibility demonstration of the actuation of a spoiler trailing edge with SMA actuators.

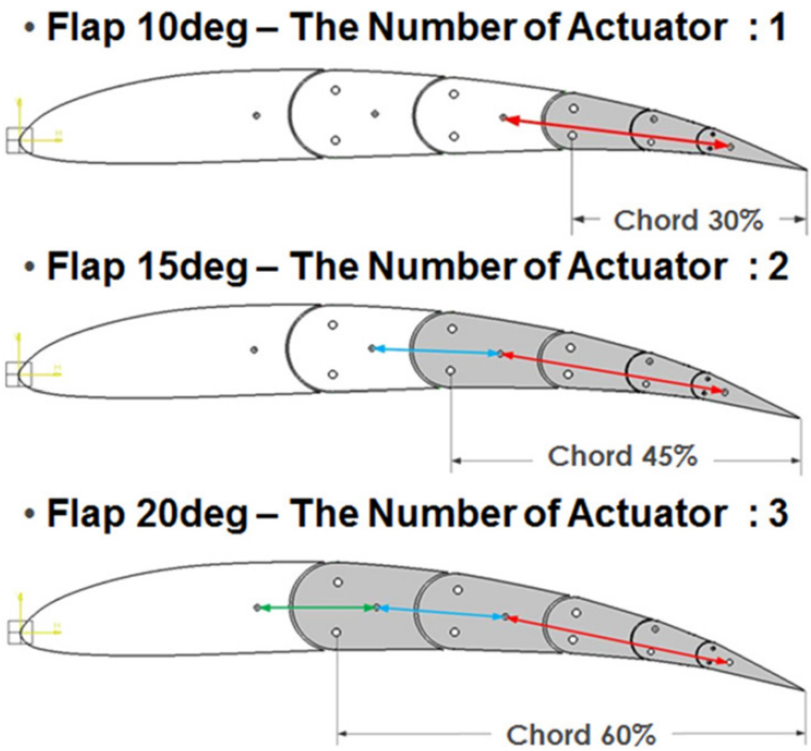



**Figure 7.** Conceptual design of SMA actuator for morphing airfoil models [101] © IOP Publishing. Reproduced with permission. All rights reserved.

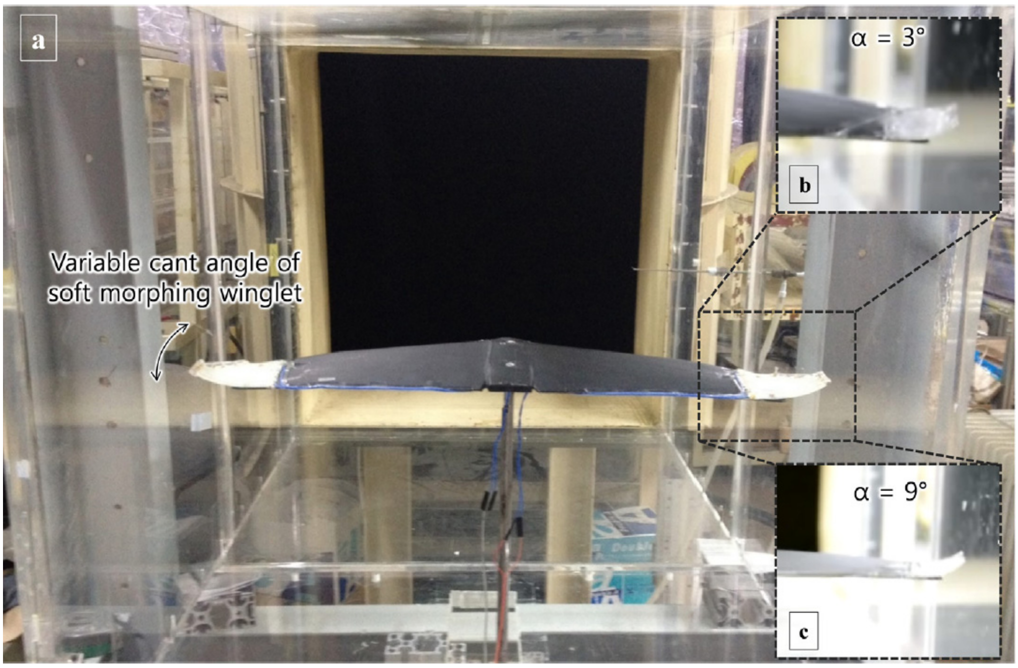



**Figure 8.** UAV with soft morphing winglets [103] Reproduced with permission from Elsevier under STM Permissions Guidelines. (**a**) wind tunnel test setup, (**b**) morphing winglet with $\alpha = 3°$, (**c**) morphing winglet with $\alpha = 9°$.

Costanza and Tata reported in a short review paper on SMA actuators for aerospace engineering, including modeling and experiments for morphing wings, inlet geometry, and tailoring of the orientation of various propulsion systems, and variable chevron shape for noise and thrust optimization [108]. Space applications for isolation of vibration, self-deployable solar sails, and low-shock release devices were proposed. Kamalakannan et al. developed a multi-segment morphing system for the micro air vehicle (MAV) using SMA actuators [109]. They applied an adaptive control algorithm that can provide fast, concurrent, and independent operation of four-segment morphing with SMA actuators. The system was implemented using an open-source autopilot with an additional weight of 6 g per segment of morphing. Kim et al., for the application of morphing flap of an unmanned aerial vehicle (UAV), proposed a hybrid composite actuator capable of maintaining the shape of an integrated SMA wire and SMP support [110]. For the improvement of the aerodynamic force in combination with the shape transformation of the wing, the proposed composite actuator was implemented as a part of the morphing wing. Through the test under wind tunnel condition, it was observed that the lift coefficients were higher by about 35%, and the drag coefficient was lower by about 50% than the conventional one. Mukherjee et al. carried out numerical simulations for the shape prediction of the trailing edge driven by a combination of SMA wires and Macro-Fiber Composite (MFC) bimorphs actuators [111]. To achieve large deflection at low frequency and rapid actuation with small deflection, an SMA wire and MFC patch was utilized, respectively. Simiriotis et al. proposed an effective methodology to design deformable wing shapes to achieve predefined target wing configurations by adjusting the applied temperature to the SMA actuator [112]. The proposed method consists of two steps: (a) a strong algorithm that can solve the coupled problem of SMA–structure in the context of a finite element analysis software and (b) the coupling of the entire process with an optimization technique to find configurations able to obtain target structures using SMA actuators. To confirm the superiority of the proposed method, numerical analysis was performed on the airfoil-based wing of the A320 model. Table 3 shows various studies on morphing wings performed using an SMA actuator. In addition, details of the morphing wing study are summarized in Table 4.

**Table 3.** Control methods for morphing wings.

| Reference | Control Type | Controller | Application |
|---|---|---|---|
| [86] | PID Control | self-tuning fuzzy controller, PID controller | morphing wing (camber) |
| [87] | | PID with on–off controller | morphing wing (camber) |
| [89,90] | | on–off and PI controller | morphing wing (camber) |
| [91,92] | | fuzzy-PID controller | morphing wing (camber) |
| [96] | | PID controller, PID with robust compensator, and PID with anti-windup compensator | Morphing wing (camber) |
| [109] | | adaptive control (PID + pulse frequency and pulse with variation) | MAV morphing planar wing |
| [82] | Passive | passive control (stress to temperature modeling) | morphing wing (camber) |
| [83] | | passive control (thermo-mechanical modeling) | morphing wing (camber) |
| [88] | | passive control | morphing wing (sweep angle change and span-wise bending) |
| [93] | | passive control | morphing wing (camber) |
| [94] | | passive control | morphing wing (camber) |
| [97] | | passive control | morphing wing (camber) |
| [100] | | passive control | morphing wing (camber) |

**Table 3.** *Cont.*

| Reference | Control Type | Controller | Application |
|---|---|---|---|
| [101] | Passive | passive control | morphing wing (camber) |
| [102] | | passive control | morphing wing (twisting of soft wing) |
| [103] | | passive control | morphing winglet |
| [110] | | passive control | UAV morphing wing (camber) |
| [111] | | passive control | morphing wing (camber) |
| [112] | | passive control | morphing wing (camber) |

**Table 4.** Investigation details of SMA applications in morphing wing.

| Reference | Vehicle | Morphed Geometry | Investigation | | |
|---|---|---|---|---|---|
| | | | Numerical | Pilot | Wind Tunnel |
| [82] | Transport Fixed Wing | camber | O | - | - |
| [88] | UAV Fixed Wing | sweep angle change span-wise bending | O | O | - |
| [83] | UAV Fixed Wing | camber thickness | O | O | O |
| [85] | MAV Fixed Wing | camber thickness | O | - | - |
| [86,87] | UAV Fixed Wing | camber thickness | O | O | O |
| [90,92] | UAV Fixed Wing | camber thickness | O | O | O |
| [93] | UAV Fixed Wing | camber | O | O | - |
| [94] | UAV Fixed Wing | camber | O | O | O |
| [96] | UAV Fixed Wing | camber | O | O | O |
| [100] | Transport Fixed Wing | camber | O | O | - |
| [101] | UAV Fixed Wing | camber | O | O | O |
| [103] | UAV Fixed Wings | dihedral/gull | O | O | O |
| [111] | UAV Fixed Wing | camber | O | O | |
| [110] | UAV Fixed Wing | camber | | O | O |
| [112] | Transport Fixed Wing | camber | O | | |

### *3.2. Other Applications to Aerospace*

Hartl et al. of Boeing has developed an active serrated aerodynamic device, variable geometry chevron (VGC), which has been installed on a GE90-115B jet engine for the Boeing

777-300 ER [113,114]. It was proved that the proposed device had a great effectiveness in noise reduction during take-off by maximizing the deflection of the chevron and also had an effectiveness in increase in the cruise efficiency by minimizing the deflection of the chevron during the remainder of the flight. Muhammad et al. proposed artificial folding wing models mimicking the hindwing mechanism of a beetle using SMA wire actuators [115]. It was confirmed that the proposed artificial hind wing had appropriate flexibility when it was flapped at a wing beat frequency of 9 Hz at a flapping angle of 120° without folding back during the flapping motion. The photographs for the demonstration of the foldable wing are presented in Figure 9. Youn et al. introduced a compressed mesh washer pyroshock isolator with the pseudoelastic characteristics of SMA wire [116]. After manufacturing of the compressed mesh washer isolators, the pyroshock isolation performances were evaluated experimentally. It was confirmed that the isolation capability can be adjustable by adjusting the pre-compressive displacement of the compressed mesh washer isolator. Kwon et al. developed a micro-vibration isolator including SMA-based mesh washer for the spaceborne cryocooler [117]. The undesirable micro-vibration disturbances induced by on-orbit operation of a spaceborne cryocooler is one of the main reasons for the deterioration of the image quality obtained from high-resolution observation satellites. Then, the micro-vibration disturbances caused by operation of the cryocooler must be effectively isolated. The mechanical characteristics of the isolator-integrated cryocooler assembly were identified via static and free vibration tests. It was experimentally demonstrated that the proposed isolator design was effective for the system under requirement temperature limits. Glücksberg et al. proposed a new concept of a releasing system using an SMA actuator for aerospace engineering [118]. Usually, the releasing and deployment maneuvers performed during launching of space satellites are executed by utilizing loads of pyrotechnics. In order to reduce high shock and vibrations and to avoid the pollution of functional instruments due to dust and gas release during explosion, they tried to replace pyrotechnic loads by others not requiring explosives. The performance of a non-explosive actuator device to cause controlled fracture of a notched bolt was analyzed using the mechanical stress generated during reverse deformation of a mechanically constrained SMA actuator.

Since the late 2010s, research on self-deploying solar sail systems using SMA has been actively reported. Costanza and Tata developed a self-deploying solar sail system using SMA wires and manufactured a small-scale prototype for the experimental evaluation [119]. In the prototype, three different structural configurations were considered and two different SMA wires were used for self-deployment of the solar sail. Costanza et al. designed and manufactured a miniaturized self-deploying system based on SMA wires integrated with a carbon fiber loom [120]. In particular, they focused on the relationship between surface–weight ratio and the deployment of the solar sail. After experimental tests with a compact prototype solar sail, it was confirmed that high surface–weight ratio values can be obtained by using light parts such as prepreg looms and rolled wires as active elements. SMA-based self-deploying solar sails manufactured by Costanza and Tata and commercial pure aluminum thin sheets with thin adhesive Kapton were used to simulate the sail. [121]. In the laboratory experiment, the effects of different heating techniques and different pressure situations on the activation time were intensively considered. Boschetto et al. fabricated four different configurations of the self-deploying solar sails, which are different for folding ways and surface reduction, and deployed configurations were analyzed by using a laser scanner to measure the planarity degree and the critical areas [122]. Bovesecchi et al. also dealt with the feasibility and reliability for the use of SMA actuators as a mechanical actuator for a solar sail self-deployment system [123]. For the activation of the SMA actuator, visible lamps were used to act out the solar radiation in space, and temperature characteristics over time were investigated for various sail configurations and environments. The folding configuration self-deployed solar sail is presented in Figure 10. The results of various applications using shape memory alloys performed in the aerospace field are summarized in Table 5.

**Table 5.** Control methods for other aerospace engineering applications.

| Reference | Controller | Application |
|---|---|---|
| [113,114] | passive control (thermo-mechanical modeling) | active jet engine (VGC) |
| [115] | passive control | MAV (flapping wing) |
| [116] | passive control (pre-compressive displacement modeling) | compressed mesh washer isolator |
| [117] | passive control | micro-vibration isolation spaceborne cryocooler |
| [118] | passive control | releasing system |
| [120] | passive control | self-deployed solar sail |
| [121] | passive control | self-deployed solar sail |
| [122] | passive control | self-deployed solar sail |
| [123] | passive control | self-deployed solar sail |

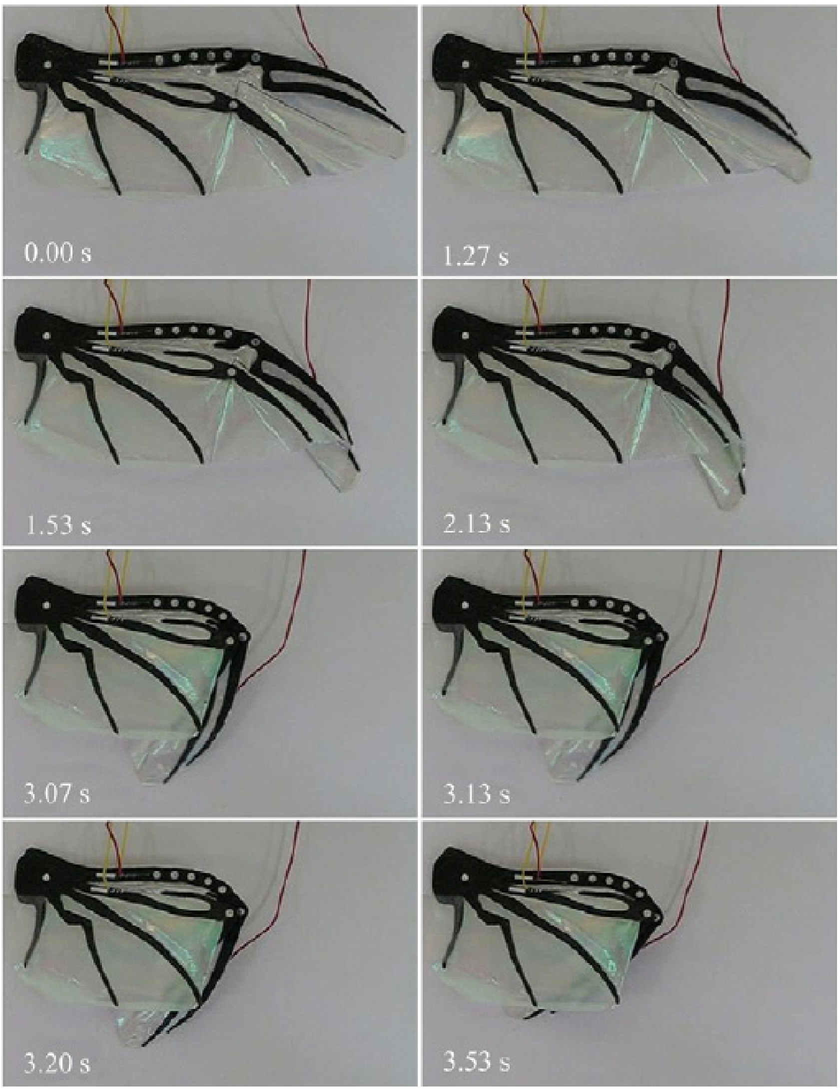



**Figure 9.** Folding action demonstration of artificial foldable hind wing [115] Reproduced with permission from Elsevier under STM Permissions Guidelines.

**Figure 10.** Folding configuration of self-deployed solar sail [123] Reproduced with permission from MDPI under STM Permissions Guidelines.

## 4. Conclusions

Structural control applications of an SMA actuator were investigated and discussed in this review article. Two main applications were vibration control of flexible structures and morphing wing application in the field of aerospace engineering. The conclusions of this review paper can be summarized as follows.

(1) In this review paper, 52 reference papers on the vibration control issue of flexible structures were investigated and evaluated. It has been confirmed that the vibration control system using SMA can be applied to various types of structures such as simple beams, flat plates, cylinders, and shell structures. It has also been known from the evaluation of five references that SMA actuators can be applied to control the vibration of a structure or building in the event of an earthquake. The use of SMA actuating technology is being increased in civil engineering fields to protect bridges and buildings from damages from severe environments. (2) The main application of SMA actuators in the field of aerospace engineering includes the morphing wing field that transforms the wing shape of an airplane. By investigating 31 articles on the morphing wing field, it has been confirmed that vibration controllability and flying stability can be enhanced by adjusting or controlling the wing shape. In addition, a review was conducted on four representative reference papers in the field of aerospace showing that the research on the self-deployed solar sail field using SMA actuators is newly and actively conducted. (3) For vibration control of flexible structures, various types of controllers have been proposed and used, from simple PID controllers to optimal controllers such as LQR to robust controllers such as sliding mode controllers. It has been found that both vibration and motion controls are well accomplished in diverse types of structural systems by employing SMA actuators. In applications in the field of aerospace engineering, simple PID controllers or passive controllers are mostly

used rather than mathematically complex controllers. Using these simple controllers or passive controllers, the morphing wing has been successfully controlled through both computation and wind tunnel experiments. (4) An iterative learning control technique is a representative competitive algorithm that has recently been newly proposed for the control of systems using shape memory alloys [124,125]. The proposed method is characterized by using only errors and previous control laws instead of using little information about the system. It is noted here that although the SMA actuator has some disadvantages such as slow response time compared with other actuators such as piezoelectric actuators, it has relatively higher control force or torque. In addition, control of multi-degree-of-system can be easily accomplished by combining several different types of SMA actuators.

However, there are still many works to be conducted for successful realizations. For example, the development of more sophisticated constitutive models, adaptable compensator design for the large hysteresis loop, efficient control strategies at wide operating temperatures, and fast computation of control input associated with deep learning method are to be explored in the future.

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