Recent researches on morphing aircraft technologies in Japan and other countries

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Abstract
Morphing aircraft technology has recently gained attention of many research groups by its potential for aircraft performance improvement and economic flight. Although the performance of conventional control surfaces is usually compromised in off-design flight conditions, the morphing technique may achieve optimal flight performance in various operations by to adaptively altering the wing shape during flight. This paper aims to provide a comprehensive review on morphing aircraft/wing technology, including morphing mechanisms or structures, skins, and actuation techniques as element technologies. Moreover, experimental and numerical studies on morphing technologies applying those elemental technologies are also introduced. Recent research on these technologies are particularly focused on in this paper with comparisons between developments in Japan and other countries. Although a number of experimental and numerical studies have been conducted by various research groups, there are still various challenges to overcome in individual elemental technologies for a whole morphing aircraft or wing systems. This review helps for researchers working in the field related to morphing aircraft technology to sort out current developments for morphing aircraft.

Keywords: Aircraft, Wing morphing, Composites, Smart materials, Flexible skins

1. Introduction
1.1 Background and brief historical review

Morphing aircraft technology has gained the attention of many research groups because of its potentials for aircraft performance improvement and economic flight. Recently, modern aircraft have been forced to be upgraded for further performance improvements due to a rising number of global air transportation under tighter economic restrictions. Modern aircraft were originally designed to enhance aerodynamic characteristics and reduce structural weight for better fuel consumption by improving the traditional wing design and integrating composite materials. However, the performance of modern aircraft with conventional designs is usually compromised in off-design flight conditions. As one of innovative technologies which may bring disruptive changes to aircraft design, morphing concepts (see Fig. 1 as an example concept proposed in (Tsushima et al., 2019a)) are introduced aiming to achieve optimal flight performance in various operations by adaptively altering the wing shape during flight. The wing morphing technique may provide further enhancements in aircraft performance to satisfy various demanding criteria for diverse missions. In the literature (Cumming et al., 2016; Nguyen et al., 2015; Pendleton et al., 2007; Tsushima et al., 2018), it is reported that the morphing technology can enhance aerodynamic characteristics and reduce structural weight and acoustic noise of aircraft. Moreover, wing morphing may reinforce flight safety by improving stall characteristics and gust load alleviation. The concept of wing shape changing was introduced long ago when the Wright Flyer (see Fig. 2), the first aircraft with an engine, controlled roll motions by manually twisting wings with wires. Although more rigid aircraft designs became popular for higher speed flight and larger payloads in following decades, the wing morphing concept was readdressed for its benefits on flight performance improvements with recent developments of structural and material technologies, which would overcome problems corresponding to the flexibility and complexity of morphing structures.

One example of modern morphing aircraft development programs is the Active Aeroelastic Wing (AAW) research program (Pendleton et al., 2007). The morphing technique was implemented to a full-scale F/A-18 fighter aircraft (see
Fig. 3) to realize wing aeroelastic twist so as to improve the aeroservoelastic effectiveness of the aircraft, instead of directly producing the maneuver loads. The program successfully demonstrated AAW technology performance and a series of experiments were conducted to obtain the aerodynamic, structural, and flight control characteristics related to AAW technology. At the same time, more substantial shape changes of aircraft components have been studied with smart materials and adaptive structures. For example, the DARPA’s Morphing Aircraft Structures (MAS) program (Weisshaar, 2006) aimed to reconcile conflicting mission requirements with shape changing active wing structures by evaluating morphing aircraft designs with three contractors. As another example, the Adaptive Compliant Trailing Edge (ACTE) flap (Cumming et al., 2016; Smith et al., 2016) was developed and tested by utilizing the morphing concept and smart materials. Piezoelectric materials were implemented to actuate the flaps, and flight tests have proven the viability of the ACTE flap to increase lift and pitch moment. More recently, the Variable Camber Continuous Trailing Edge Flap (VCCTEF) system (Kaul and Nguyen, 2014; Nguyen et al., 2015) has been studied as one of the wing morphing applications to a commercial aircraft design. The performance improvement by the VCCTEF system was evaluated with aerodynamic numerical simulations and wind tunnel tests. They observed performance improvements by the VCCTEF system with respect to drag reduction and high-lift up to 6.31%. Cellular twist morphing is another approach to reshape a wing (Benjamin et al., 2017). This method utilizes lattice-based cellular composites for an active twist wing with servo actuators. The air vehicle with the cellular twist wings have been tested in the wind tunnel as well as flight testing. Their experiment also demonstrated stall mitigation capability. In Europe, the Smart High Lift Devices for Next Generation Wings (SADE) project evaluated the potential of morphing techniques. The project focused on morphing technologies for the leading and trailing edge high-lift devices (Di Matteo and Guo, 2011; Kintscher et al., 2011).

In addition to the abovementioned projects, there are a number of works on morphing technologies, some of which can be found in literature (Barbarino et al., 2011; IADF, 2013; Sofla et al., 2010; Tamayama, 2009; Weisshaar, 2013). Most modern morphing technology programs have been commissioned in Europe and the United States. However, a similar concept is adapted in Japan as well. For example, the Mitsubishi A6M Zero Fighter implemented an adaptive aeroservoelastic technique (Horikoshi, 1966). The concept was to deliberately reduce control system stiffness and shift aeroservoelastic characteristics so as to achieve optimal maneuverability in wide range of flight speed. Recently, many Japanese research groups have also actively studied morphing technology. This article introduces most recent works on the morphing aircraft technologies by comparing such researches in Japan and other countries.

![Traditional wing](image1.png) ![Corrugated morphing wing + Piezoelectric actuator](image2.png)

**Fig. 1** An example concept of a corrugated morphing wing.

![Fig. 2 The Wright Flyer.](image3.png)
1.2 Benefits/roles of morphing

Including the abovementioned research projects, previous works on morphing technologies have proven various benefits of morphing aircraft (Barbarino et al., 2011; IADF, 2013; Sofla et al., 2010; Tamayama, 2009; Weisshaar, 2013). Although they are limited, the main benefits obtained by the technologies are as followed:

- Drag reduction
- High-lift performance
- Structural weight reduction
- Acoustic noise reduction
- Improvement of control power/effectiveness
- Capability of multiple missions with a single airplane

Compared to conventional aircraft, morphing aircraft can adapt to various flight conditions and provide optimal flight performance for a variety of missions by eliminating design compromises. In addition, blending of morphing and smart structures in an integrated form can further reduce design compromises in conventional control surfaces and improve aircraft performance. There are many schemes to achieve improvements on aerodynamic, structural, or control performances, or some/all of them, through the wing morphing techniques. Those strategies will be introduced in the next section.

1.3 Categories of morphing

To achieve performance improvements of aircraft as explained above, there are several concepts for wing morphing. The wing morphing schemes can be classified into three major categories as shown in Fig. 4: planform, airfoil, and out-of-plane morphing. In the planform morphing types, three different sub-categories of geometry changes have primarily been studied as the span and chord length alteration and sweep angle change of the wing. This type of morphing effects on the effective surface area of wing and adjust an aspect ratio and sweep angle of wings during flight. The second morphing type includes the geometry changes of the airfoil camber and thickness profiles. This kind of wing morphing directly adjusts the airfoil profile during flight so that optimal aerodynamic characteristics can be obtained in a wide range of flight envelope. In addition, by replacing the traditional control surfaces such as ailerons, flaps, and slats by a smooth morphing airfoil, the reduction of structural discontinuities may lead to additional performance improvements such as acoustic noise and drag reductions. The last type relates to transform dihedral and anhedral angle of the wing as well as the twisting and spanwise bending of the wing. This category can change aerodynamic characteristics of wings by shifting the wing positions out of the original plane. A realization of those morphing schemes requires multidisciplinary developments in a wide range of fields. This article focuses on mechanisms and structures, skin designs, and actuation technologies to achieve wing morphing.

2. Element technology 1: Morphing mechanisms/structures

Although there are many concepts integrating smart materials and structures to realize morphing aircraft/wings, there are also approaches for morphing to extend traditional designs. The VCCTEF system may be one of representative recent designs to accommodate traditional commercial aircraft taking advantage of the morphing wing concept (Ferrier et al., 2018; Hashemi et al., 2018; Nguyen et al., 2018). The VCCTEF system achieved the circular wing camber by implementing three chordwise control surface segments of equal chord length, which resulted in a smooth chordwise...
pressure distribution. For a small UAV, Ajaj et al. (Ajaj et al., 2016) developed a span length morphing concept named the Gear driveN Autonomous Twin SPAR (GNAT Spar). The design augmented the span morphing capability to their rigid wings with a rack and pinion actuation system. Their wind tunnel test showed that the span extension increased aerodynamic efficiency although the concept still had problems in actuation forces due to the flexible skins in their design. On the other hand, a multi-slotted variable camber morphing wing configuration has been studied in Japan to improve flight safety of aircraft as shown in Fig. 5. The camber of the wing can be altered by spreading or closing the wing segments. The wind tunnel tests showed higher lift characteristics and a largely extended stall margin compared to a traditional wing with leading edge slats and trailing edge flaps (Maki, 2016). Aso and Tanaka proposed a concept of effective twist morphing spar (see Fig. 6) to achieve an arbitrary distribution of the twist angle. Their experiments and numerical simulations partially demonstrated the feasibility of the design concept although further investigations of design validity considering external loads such as the aerodynamic lift should be performed (Aso and Tanaka, 2017). These approaches have promising results for aerodynamic efficiencies, but they usually require complicated systems to achieve wing morphing.

Fig. 4 Categories of morphing.

Fig. 5 Wind-tunnel model of multi-slotted variable camber morphing wing (Maki, 2016).

Fig. 6 A concept of effective twist morphing spar (Aso and Tanaka, 2017).
Bi- or multi-stable structures have more than two stable configurations corresponding to local minima of the strain energy (Cappello et al., 2014). Those structures can be utilized to design morphing structures which has more than two operation shapes. Andres et al. studied bi-stable twisting I-beam (Andres et al., 2018). The structures showed a potential in aerospace applications to produce large deflections and rotations without the continuous actuation. Eckstein et al. analytically and experimentally studied the nonlinear temperature-curvature relationship of composite bimorph shells (Eckstein et al., 2016). Snap-through behavior of the composite shell taking advantage of temperature change was demonstrated using fiber-metal hybrid laminates. Boston and Arrieta have used selectively stiff structural members to achieve efficient morphing (Boston and Arrieta, 2018). The stiffness characteristics of a structure can be altered by means of locally bi-stable components. They employed finite element analyses to perform a parametric study of structural design for bi-stable components. In a Japanese research group, Senba et al. investigated two-way actuation of bi-stable composites by introducing macro fiber composite (MFC) actuators (Senba et al., 2010). They could generate dynamic buckling by tuning the excitation frequency of MFC for each of composite stable condition as shown in Fig. 7. Multi-stable designs can provide multiple stable configuration in a structure with a relatively simple mechanism, which have a potential to reduce structural weight. Challenges for approaches using this kind of design are how to securely avoid accidental snaps from one configuration to another with unexpected external loads and balance structural characteristics in each stable configuration, while setting an appropriate switching between configurations.

![Fig. 7 Bi-stable laminate with MFC actuator (Senba et al., 2010).](image)

Morphing structures can also be realized by deliberately designing structures consisting of compliant mechanisms. The Mission Adaptive Compliant Wing (MACW) was developed using this approach (Kota et al., 2009). The wing implemented compliant mechanisms in the trailing edge flap to control the airfoil camber shape. The MACW was intended to be used for High Altitude Long Endurance (HALE) aircraft, and the performance of MACW was flight-tested by mounting the MACW under the fuselage of White Knight aircraft. They stated that optimizing the wing L/D continuously during the mission would expand the “laminar bucket” capability and improve the flight range by 15% or more. Wang et al. proposed a compliant structure with a concept of unsymmetrical stiffness for a morphing winglet (Wang et al., 2016). The actuation is a linear actuation force. The stiffness asymmetry was achieved by using different composite layups of round corrugation structures. Among Japanese research groups, Kambayashi et al. introduced the multi-layered compliant mechanism to improve the control performance of wing trailing edge morphing deformation as shown in Fig. 8 (Kambayashi et al., 2018). Each layer was forced by individual actuation load. They applied this idea to two-dimensional topology optimization analysis and confirmed its accuracy by conducting three-dimensional FEM analysis. Taguchi et al. investigated aerodynamic characteristics of morphing wing model passively deformable by dynamic pressure by 2D wind tunnel test (Taguchi et al., 2018). Their unique wing model had the trailing edge portion made of flexible materials, and upper and lower surface connected by spokes inside the airfoil. The wing model deformed with dynamic pressure so as to increase the camber. Their investigations found that the deformation of the morphing wing model differed depending on the spoke arrangement although they still need a further detailed investigation for the wing performance. Optimal compliant mechanisms tend to become complex structures and are not easily fabricated. One possible solution for fabrication would be additive manufacturing. This developing technology would provide the capability to manufacture very complicated designs. However, the technique is sufficient for making prototypes but still has not matured enough for final products.
Corrugated structures are one of the popular designs in compliant structures for wing morphing. They simplify and effectively form lightweight flexible structures which can be applied for morphing wings. Dayyani et al. provided a comprehensive review of the literature on such corrugated structures, presenting broad ranges of applications (Dayyani et al., 2015). Molinari et al. studied the aerodynamic and structural performance of a morphing wing concept through their simulations and experiments (Molinari et al., 2016). Their wing model consisted of fully compliant structures and solid-state piezoelectric actuators. They used corrugated structures as the lower skins of their wing to achieve changes in the length of the airfoil perimeter. Yokozeki et al. have been actively worked on studies of morphing wings with corrugated structures as one of Japanese research groups (Yokozeki et al., 2014). They constructed a morphing wing with corrugated trailing edge, which allowed wing camber morphing by pulling wires connected to the trailing edge with a servo actuator as shown in Fig. 9. Their simple corrugated morphing wing proved the feasibility and capability of camber morphing with a simple actuation mechanism. Their wing tunnel tests also showed lift increase with morphing configuration of the variable camber wing compared to the conventional wing with a hinged control surface in a similarly deflected configuration. Nakamura et al. studied an optimization of such morphing wings with corrugated structures to maximize the lift-to-drag ratio or lift coefficient (Nakamura et al., 2018). They used radial basis function network with a concept of tabu search to obtain optimal design candidates. Corrugated structures can provide flexibility to wings if they are appropriately integrated. However, ill-designed corrugated structures would become too flexible to resist aerodynamic loads and result in requiring analysts/designers to consider a control mechanism to maintain morphing shapes and perform comprehensive optimizations. In addition, corrugated structures need to be closed by a certain skin system to obtain smooth surfaces, which would be another challenge. In next section, the literature on such flexible skin technologies for morphing wing is reviewed.

3. Element technology 2: Morphing skins

Morphing structures, which provide flexibility for wing morphing and load-bearing capability against aerodynamic and other external loads simultaneously, can be realized by utilizing technologies discussed in the previous section. Those structural designs would work as skeletons of a wing, but a wing system still requires a certain skin mechanism to enclose those skeletons for efficient aerodynamic characteristics, while avoiding adverse structural effects for wing morphing. Overviews of studies focusing on skin technologies for morphing structures can be found in the literature (Ding and Shen, 2018; Thill et al., 2008).

One of candidates for skins used in morphing structures is elastomeric skins. Falken et al. manufactured Elastomeric Prepreg (ePreg), which had a high ductility of elastomeric matrix with ethylene propylene diene monomer (EPDM)
rubber and high tensile strength with carbon fiber. They performed tensile, single lag shear, 3-point bending, fiber-bundle pull-out, and wrinkling/shear frame tests to establish newly designed material database, the detailed descriptions and results of which can be found in their works (Falken et al., 2016). Another design approach is to utilize auxetic materials, which exhibit a counter-intuitive behavior with uncommon material properties. For example, auxetic materials with such as negative Poisson’s ratio may expand transversely under uniaxial tension loads. Those materials have potential to provide desirable properties attributed to such exotic behaviors. Ren et al. provided a review of recent progress of auxetic metamaterials and structures (Ren et al., 2018). They concluded that those auxetic materials had not been in the practical state since manufacturing and fabrication of those auxetic materials required very high cost and some mechanical properties of auxetic materials were sacrificed to achieve desirable properties. Recently, Attard et al. demonstrated a behavior of chiral honeycombs having a negative Poisson’s ratio to form dorm-like structures with simple prototypes as well as a simplified mathematical model (Attard et al., 2018). A Japanese researcher, Saito, and his colleagues studied arbitrary cross-section composite honeycomb cores based on origami technique. Especially, they used the concept of the kirigami honeycomb, which was made from periodically assembled single flat sheets (Saito et al., 2014). Also, in a Japanese research community, Natori et al. discussed deployable one- and two-dimensional structures based on folding patterns especially in consideration of deployable elements in nature for space applications. Figure 10 shows an example of such structures, “IKAROS” developed by Japan Aerospace Exploration Agency (JAXA) (Natori et al., 2015). In Europe, a design of a morphing leading edge for a twin-prop regional aircraft was studied by Ricci et al. to fulfill high-lift requirements with a natural laminar flow wing (Ricci et al., 2018). In their multidisciplinary project, composite corrugated skins were evaluated in terms of morphing shape realization and structural stiffness as shown in Fig 11. Shape memory polymers (SMPs) have also been considered as a candidate for morphing skins. In Japan, Senba et al. applied small patched SMP films to large membrane structures in order to improve membrane surface shape (Senba et al., 2013). Out-of-plane displacement in slacking area were drastically improved with SMP films. Rahman et al. further studied chopped glass fibers used in shape memory polymer composites (SMPC) as a medium to reinforce the polyurethane matrix (Rahman et al., 2017). They showed the increasing inflexibility of SMPC against the deformation with the amount of grass fibers, though the strength of SMPC improves. Although tremendous design efforts for morphing skins have been conducted for potential use for a morphing wing, there still is a limitation to overcome contradictory demands of morphing to maintain the stiffness of a morphing structure for external loads while the skin should correspond to the varied geometry.

Fig. 10 Pictures of the deployable solar sail demonstrator “IKAROS” (Natori et al., 2015).

Fig. 11 Model of the leading-edge corrugated skin (Courtesy of Prof. Sergio Ricci, Politecnico di Milano (Ricci et al., 2018)).
4. Element technology 3: Morphing actuations

While most morphing wing models implement traditional servo actuators, the use of smart materials has also been considered as an alternative. Donadon and de Faria studied the aeroelastic stability of Shape Memory Alloy Hybrid Composite laminates (SMAHC) (Donadon and de Faria, 2016). Shape memory alloy (SMA) wires and carbon fibers were embedded into a polymeric matrix to construct the SMAHC as a three-constituent composite material. Their study showed that the changes in the fraction of martensite/austenite transformation phases of the SMA induced the stiffening effect, which resulted in stabilization of the plate. Driesen et al. demonstrated a wing morphing with antagonistic SMA wire (Driesen et al., 2018). Their experiments showed a significant shape change in airfoil profile within a second of actuation. They also performed wind tunnel tests, which showed a promising performance of SMA-based wing morphing to replace a conventional wing with hinged flaps. Leal et al. studied SMA wires embedded into an elastomer matrix as an actuator for morphing wing (Leal et al., 2018). The SMA actuators were further integrated into the skin of an airfoil so as to provide a continuous outer mold line without hindering morphing capability. The experiment results showed a sufficient force to induce wing morphing under aerodynamic loads in a wind tunnel test. Recently, Koga et al., a Japanese research group, demonstrated a morphing flap driven by antagonistic SMA wires with their morphing wing model as shown in Fig. 12 (Koga et al., 2018). They also explored a relationship between the pre-strain given to SMA wires and available stroke in their wing model. Through their experiments, they proposed an optimal pre-strain in antagonistic SMA wires. SMAs may generate enough force for wing morphing, but there seems to be a room for improvements in their response speed. Ikeda et al. proposed a control method to reduce energy required to actuate SMA by means of hysteresis in stress-strain-temperature relationship of SMA as shown in Fig. 13. Their works showed feasibility of the proposed control method experimentally and numerically (Ikeda et al., 2018).

Piezoelectric materials have properties that change their geometry corresponding to an externally applied electrical loading. Due to their fast response and wide band-width, they are also considered as an alternative actuator for wing morphing. Molinari et al. proposed a morphing wing concept integrating the compliant structures and piezoelectric MFC actuators (Molinari et al., 2016). Bimorph piezoelectric actuators were installed on the upper skins to allow camber morphing of the wing with compliant structures. They successfully demonstrated the capability of wing morphing and variations in lift coefficient with their wing concept. Andres et al. studied the design and utilization of the nonlinearity of bi-stable twisting I-beam with low strain piezoelectric actuator (MFC) (Andres et al., 2018). They explored an optimum
positioning of the piezoelectric actuator and proposed dynamic actuation strategy for the system to achieve fast and large deflections. Japanese researchers have also worked on such piezoelectric materials. For example, Senba et al. implemented MFC actuators for two-way actuation of bi-stable composites (Senba et al., 2010). The micro force generated by the MFC could induce dynamic snap-through of the bi-stable composite. Tsushima et al. proposed an electro-aeroelastic analysis framework to investigate aeroelastic characteristics of morphing wing with MFCs (Tsushima et al., 2019a). Their investigation showed a potential of MFCs to morph the corrugated wing (see Fig. 14). By using active fiber composites (Bent, 1999), Tsushima et al. also studied the performance of an integrated composite morphing wing with piezoelectric actuation as shown in Fig. 15 (Tsushima and Su, 2016; 2018). It was found that such a wing could successfully suppress aeroelastic instabilities and vibrations due to external gust disturbances.

![Fig. 14 An experimental setup of a corrugated structure with MFC (Tsushima et al., 2019a).](image1)

![Fig. 15 A model of piezoelectric active composite morphing wing (Tsushima and Su, 2018).](image2)

Some research groups have studied a potential use of other actuation systems for morphing wing. Nigam et al. used pneumatic actuator for multiple morphing scheme including telescopic, sweep, twist, and dihedral/anhedral morphing (Nigam et al., 2016). Their wind tunnel tests and numerical analysis showed that the capability of shape morphing with the pneumatic actuators. Chen et al. proposed a morphing skin embedded with pneumatic muscle fibers (Chen et al., 2011). Their experiments showed that the pneumatic muscle fibers could provide a contraction ratio up to 26.8%. They also investigated the output force of the morphing skin resulting 17.8% contraction ratio, which would be sufficient for a camber morphing with maximum strain level below 2%. Suzuki and Kamamichi studied an artificial muscle actuator called as a twisted and coiled polymer actuator (TCPA) or super coiled polymer actuator, which can be thermally actuated (Suzuki and Kamamichi, 2018). To address problems related to the cooling speed, they utilized an antagonistic structure and validated their simulations with experiments. Actuations by utilizing smart materials have advantages in the actuation mechanisms. Those materials can be easily embedded or integrated in the structures to be actuated without huge modification in the overall structure design. On the other hand, smart materials are not perfect devices and also have drawbacks in their actuation power, required energy, response speed, and so on. One of the challenges in actuation with those materials would be how to optimize the device’s performance while guaranteeing the actuation system requirement.

5. Experiments and numerical analysis of morphing aircraft

There exist a variety of morphing wing concepts. Feasibility and capability of those conceptual morphing wing designs have also been validated or demonstrated with various demonstrators as well as diverse numerical analysis methodologies. In this section, recent experimental results of morphing technology demonstrators, experimental techniques, and numerical studies using elemental technologies discussed in the previous sections are introduced.

Gabor et al. studied an adaptive upper surface wing representing a wing tip section by comparing their CFD analysis
and wind tunnel tests (Gabor et al., 2016). The adaptive wing used flexible carbon fiber composite skins with electric actuators for upper skin morphing. Both CFD and wind tunnel test results showed an increase of laminar flow region with a design optimization delaying the transition location. Tomić et al. presented a fiber-optic interferometric technique for a measurement of deflections of an aircraft’s morphing wing (Tomić et al., 2018). The proposed technique achieved an accurate deflection measurement in their experiments. Olson proposed a numerical analysis framework to access flight loads of a Part 23 Cessna Model 525B business jet with active winglets, ATLAS® (Active Technology Load Alleviation System) developed by Tamarack® Aerospace Group (Olson, 2018). By accounting for actual flight test data, Nastran’s doublet-lattice flight loads model was modified to take into account uncertainty. Their framework was then validated by comparing with other flight test cases. Dussart et al. studied roll performance of a generic aircraft with morphing wingtip, which was a type of folding structures (Dussart et al., 2018). They conducted aeroservoelastic simulations and showed the influence of aerodynamic derivatives caused by control and flight parameters. They demonstrated that a change in aerodynamic derivatives was affected by wingtip size and airframe flexibility. Jasa et al. optimized not only wing and morphing inputs, but also a mission trajectory at the same time for a morphing Common Research Model wing (Jasa et al., 2018). They stated that a fuel burn could be decreased by 0.2 to 0.7% with their optimized model compared to a non-morphing case. They also conducted a surrogate-based optimization approach. However, the performance calculated was not agreed to the fully coupled optimization process. They concluded that if it was strongly coupled systems or path-dependent optimization problems, the fully coupled approach was preferable. Quintana et al. investigated a morphing performance from the aerodynamic point of view for a conceptual morphing micro UAV, which had an ability of wing spanning and sweeping motions (Quintana et al., 2018). In a variety of scenarios, they varied a transition period between these two motions. They concluded that the optimal performance was obtained with a six second transition with a delay in sweeping motion. Ding and Shen conducted a sectional design optimization of a helicopter blade having Continuous Trailing-edge Flap (CTEF) (Ding and Shen, 2018). They applied aeroelastic analysis to their study. The objective of this study was to maximize the pitching moment coefficient. They compared the performance of CTEF blade with that of conventional Discrete Trailing-edge Flap (DTEF). The aerodynamic performance of CTEF was slightly behind that of DTEF, although the cases of DTEF took no account of energy loss.

Experimental studies for morphing wing have also been performed by Japanese research groups. For instance, Asanuma and Tezuka experimentally studied influences of different deformation areas on the aerodynamic characteristics of morphed airfoils at the Reynolds number 5000 (Asanuma and Tezuka, 2018). They reported based on their experiments that the gradient of lift coefficient for morphing wings could be maximized by moving a laminar flow separation point closer to the trailing edge. Tani et al. performed wind tunnel test to investigate performance of acoustic noise reduction by a morphing wing, whose slotted flaps were replaced with camber morphing trailing edge without any slots between the main wing and the morphing trailing edge sections (Tani et al., 2018). They also studied a morphing slat cove filler configuration to further enhance the noise reduction performance. Their test results showed that their morphing wing model successfully suppressed the slat noise at specified frequency ranges. In addition, as a numerical study, Jinden et al. applied an inverse method to design aerodynamic shapes of morphing wing (Jinden et al., 2018). The method had a potential to provide optimal design shapes with a very low computational cost so as to realize a real-time control. Hanada et al. evaluated the applicability of morphing flap to an amphibious aircraft using the potential solver named as PANUKL (PANeli UKLad) developed at Warsaw University of Technology (Hanada et al., 2018). The performance of generating lift force by a morphing flap was improved compared with one of conventional flap although the influence of nonlinear aerodynamic forces could not be considered in the potential solver. Tsushima et al. developed an integrated aeroelastic analysis framework for dynamic analysis of morphing wing with corrugated structures (Tsushima et al., 2019b). The framework integrated the corotational shell finite element approach to consider geometrical nonlinearity, which was coupled with the unsteady vortex lattice method. On the other hand, Soneda et al. proposed a different analysis framework to evaluate aeroelastic behaviors of camber morphing wing using corrugated structures (Soneda et al., 2018). They used XFOIL (Drela, 1989) and a CFD solver, UTCart (Takahashi and Imamura, 2013), developed by Massachusetts Institute of Technology and the University of Tokyo, respectively, for aerodynamic load calculations. The aerodynamic solvers were coupled with their flexible 2-D beam equations (Satoh and Yokozeki, 2017). Tashiro et al. studied a method for load control using superposition (LCS) (Tashiro et al., 2018). Their computationally efficient numerical method was verified in linear deflection regime by compared with direct solutions obtained by MSC.Nastran and Tsushima’s nonlinear framework. An optimization study was also carried out using the LCS method. Yoshida et al. constructed the procedure to calculate unsteady aerodynamic forces for structures varying their structural parameters, which was often shown in a
parametric study of morphing structure, for the purpose of conducting flutter simulations (Yoshida et al., 2018). They could derive the forces through their method although they could not gain high accuracy. Otsuka and Makihara introduced an aeroelastic analysis framework for flexible and deployable structures using an approach of multibody dynamics (Otsuka and Makihara, Published online 2018). Multibody dynamics was coupled with the nonlinear finite element method, which was absolute nodal coordinate formulation (ANCF). This framework allowed the study of the dynamics of deployable wing aircraft with complicated cross-section bodies.

As described above, experimental studies on morphing technology performed by Japanese research groups use wing models or more simplified structures to evaluate capabilities and performances of individual elemental technologies. The results and findings from those studies are used as a foundation for numerical analyses to evaluate a more comprehensive performance of morphing wings involving several engineering fields in structures, materials, and actuations. On the other hand, studies on morphing technology in other countries cover experiments with wing models, numerical analyses with conceptual designs, and a few demonstrations with a whole aircraft implementing morphing technology. The results from the previous studies with the integrated morphing technology can be beneficial to explore actual and comprehensive performance of morphing aircraft. Those developments from research projects in Japan and other countries should be fully utilized to push forward the morphing technology and to realize future practical and efficient morphing vehicles.

Fig. 16 A morphing wing model with a belt-rib concept (Taguchi et al., 2018).

6. Conclusions

This paper aims to provide a comprehensive review of morphing aircraft/wing technology, including morphing mechanisms or structures, skins, and actuation techniques as element technologies. Moreover, experimental and numerical studies on morphing technologies applying those elemental technologies are also introduced. Recent studies of related technologies are particularly focused in this paper with comparisons between developments in Japan and other countries. Optimal compliant mechanisms tend to become complex structures and are not easily fabricated. One possible solution for fabrication would be additive manufacturing. This developing technology would provide the capability to manufacture very complicated designs. The technique is sufficient for making prototypes but is still not matured enough for final products.

Morphing structures using mechanical, bi- or multi-stable, and compliant (including corrugated structures) designs are reviewed. Mechanical morphing designs have promising results for aerodynamic efficiencies, but most of them are extensions of traditional systems and mostly resort to complicated systems to realize wing morphing. Approaches using multi-stable structures can provide multiple stabilities in designed configurations, but transitions between phases should be carefully treated. Otherwise, unintentional transitions of phases with unexpected external loads may lead to catastrophic accidents. A compliant mechanism is one of popular methods to achieve wing morphing since it is usually designed to obtain optimal deformation shapes for wing morphing. Therefore, the optimization process is the key to determine the performance of morphing wings with compliant structures. Design outcomes of optimization processes are usually sophisticated structures, which are hard to manufacture or fabricate. As a consequence, a fabrication method for such structures is also a challenge in the development of morphing wings. An additive manufacturing might be an option. There are other schemes such as a passive morphing wing with a belt-rib concept as shown in Fig. 16 (Taguchi et al., 2018). Studies of those schemes have not been fully explored yet, and further investigations would be necessary.

Morphing skin technology, studies of elastomeric, auxetic, and corrugated skins as well as skins using SMP are presented. The main challenges of skin developments are the diverse requirements for a morphing skin. Although tremendous design efforts for morphing skins have been conducted for potential use for morphing wing, performance of
those skins are still limited to satisfy a requirement of morphing to maintain stiffness of a morphing structure while complying with the varied geometry.

Actuation technologies using mechanical, SMA, and piezoelectric materials as well as other actuation schemes with pneumatic and artificial muscle actuators are introduced. Smart materials have a potential to improve performance of integrated structure by reducing structural weight. However, piezoelectric materials are constrained in deformation scale and actuation force although their response speed and high bandwidth would be effective in vibration controls. Consequently, an integration of morphing structure and piezoelectric materials should be carefully designed to produce large deformation if those materials are used as morphing actuators. On the other hand, SMAs seemed to provide sufficient force to actuate a morphing wing with limited response speed. Therefore, further improvements in such actuations with SMAs are also important. There are only a few developments using other actuation mechanism such as pneumatic or artificial muscle actuation, so more detailed studies would be necessary to evaluate performance of those actuations.

Recently, a number of experimental and numerical studies have been conducted by various research groups as introduced in the previous section. Nevertheless, there are various challenges to overcome for a whole morphing aircraft or wing systems. For example, although various morphing mechanisms demonstrated actual morphing capability, those morphing mechanisms still need to consider effective actuating solutions and enclosing skins and evaluate comprehensive performance including structural weight, power consumptions, and aerodynamic efficiency to achieve cost-effective and superior performance to traditional aircraft and wing designs. Therefore, it is very important to start integrating those elemental technologies to develop comprehensive morphing devices. Some of the studies have already tackled on those multidisciplinary problems involving morphing mechanisms, skins, actuations, as well as controls. However, only a limited number of works have reached to an actual realization of morphing aircraft/wings and flight demonstrations. With the concept of morphing aircraft/wings numerically investigated and other elemental technologies, we need to start building the blocks to develop practical and efficient morphing aircraft.

The authors are strongly looking forward to seeing morphing aircraft using one or some of the key technologies introduced in this paper realized in the near future, and hope that this review helps researchers working in the field related to morphing aircraft technology to sort out current developments for morphing aircraft.

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