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REVIEW ARTICLE

Design and applications of morphing aircraft and their structures

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ABSTRACT Morphing aircraft can adaptively regulate their aerodynamic layout to meet the demands of varying flight conditions, improve their aerodynamic efficiency, and reduce their energy consumption. The design and fabrication of high-performance, lightweight, and intelligent morphing structures have become a hot topic in advanced aircraft design. This paper discusses morphing aircraft development history, structural characteristics, existing applications, and future prospects. First, some conventional mechanical morphing aircraft are examined with focus on their morphing modes, mechanisms, advantages, and disadvantages. Second, the novel applications of several technologies for morphing unmanned aerial vehicles, including additive manufacturing for fabricating complex morphing structures, lattice technology for reducing structural weight, and multi-mode morphing combined with flexible skins and foldable structures, are summarized and categorized. Moreover, in consideration of the further development of active morphing aircraft, the paper reviews morphing structures driven by smart material actuators, such as shape memory alloy and macro-fiber composites, and analyzes their advantages and limitations. Third, the paper discusses multiple challenges, including flexible structures, flexible skins, and control systems, in the design of future morphing aircraft. Lastly, the development and application of morphing structures in the aerospace field are discussed to provide a reference for future research and engineering applications.

KEYWORDS morphing aircraft, additive manufacturing, lattice structure, smart material, flexible structure, flexible skin

1 Introduction

Conventional aircraft exhibit many shortcomings when they operate in increasingly complex service environments; for example, their performance is optimized under a given flight condition or compromised under different flight conditions, which means aircraft performance is suboptimal when loads, flight attitudes, or flight missions change [1,2]. Observation of flying animals, such as birds, indicates that when they transition from a high-speed cruise to a fast maneuver and then to a stable landing, their wings and tails change shape, allowing them to perform multiple flight tasks with consistent best conditions [3–5], as shown in Fig. 1 [6–8]. Inspired by this behavior, morphing aircraft were proposed as a means to perform different missions during one flight while maintaining optimal performance, and they have become an important trend in the design of future aircraft.

The Morphing Aircraft Structures (MAS) program defines a morphing aircraft as a multirole platform that can adapt to environmental changes with state changes [9]. Most of the lift of aircraft is created by the wings, so modifying their parameters, such as wingspans, airfoils, and sizes, can considerably affect aircraft performance [10]. As a result, morphing aircraft designers focus on the wings, and only a few designs have morphing tails or fuselages. With the different deformation forms of the wing structure as a reference, the development of morphing aircraft can be divided into three parts.

The first part refers to variable-geometry structures. It

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Fig. 1 Birds' different flight attitudes for different tasks: (a) cruising [6], (b) diving [7], and (c) landing [8].

can be traced back to the Wright Flyer, the first airplane invented by the Wright Brothers, which had flexible wings that twisted like birds [11]. However, carrying capacity and stability were key issues because of the wooden structure of the aircraft. Therefore, airplanes with all-metal structures were built [12], and rigid structures have become prevalent due to the increasing demand for cruise speed and payload. Flexible morphing aircraft structures have evolved into compromised wing geometries with rigid control surfaces, such as flaps, ailerons, and slats, and these rigid structures make up the modern mainstream of fixed-wing aircraft [13]. In brief, the first part describes early morphing aircraft where only the geometry of the wings is changed on a small scale.

The second part refers to variable-configuration structures, and it began in the 1930s [14] when researchers developed large-scale morphing aircraft that could modulate their wing configuration during flight to enhance multitasking adaptability. The conventional wing has a limited overall performance, especially multitasking performance, because it has a compromised design [15]. For example, low-speed aircraft require high aspect-ratio wings to increase the lift-to-drag ratio (L/D) and reduce aerodynamic-induced drag for long ranges and low fuel consumption [16,17]. For high-speed, especially supersonic, aircraft that require high stability and maneuverability, wings with low aspect ratios and high sweep angles are needed [18,19]. Consequently, the optimal service range is limited by the wing configuration, resulting in the constant presentation of novel schemes that can considerably alter aerodynamics. These schemes can be divided into three categories in terms of morphing degrees of freedom: planform, airfoil, and out-of-plane morphing [20]. These categories and their advantages are listed in Table 1 [10,11,13,21–30]. In summary, this part presents rigid and mechanical morphing technologies, which have also been applied to fuselages [31], engines [32], and inlets [33].

The third part refers to smart structures that accompanied the development of smart materials in the 1980s [34]. Smart materials demonstrate self-sensing, self-adaptive, or self-repairing capabilities when confronted with external stimuli [35,36]. Smart structures driven by a wide range of smart materials, such as shape memory alloys (SMAs), piezoelectric materials, and magnetostrictive materials, have been investigated and applied by morphing aircraft designers [37,38]. Since then, many programs for morphing aircraft with smart material actuators have been implemented due to the new research interest in lightweight, flexible, intelligent, and multipoint optimal aircraft [39]. Compared with rigid and mechanical morphing technologies, flexible and structural morphing technologies enable aircraft to make their systems lighter and complete the deformation process more efficiently and continuously, which can delay flow separation, enhance lift, and reduce drag, fuel consumption, noise, and emissions [40,41]. Topology optimization, additive manufacturing (AM), and composite technologies support the design of smart materials and structures [42–44].

Although the three parts began at different times, none has been terminated because no research has identified the best among them. However, flexible morphing modes are popular, as evidenced by the conceptual designs proposed by prominent research institutions (Fig. 2) [45–47]. Morphing aircraft design is beneficial but

Table 1 Categories and advantages of morphing wings

Categories	Methods	Advantages	Typical examples
Planform	Sweep	Increased critical Mach number; decreased high-speed drag	F-14, F-111, Mig-23, Su-24, B-1A [21,22]
	Span	Increased L/D, cruise time, and distance; decreased engine requirements	MAK-10, MAK-123, FS-20 [23]
	Chord	Increased low-speed performance	LIG-7 [13]
Airfoil	Camber	Increased wing efficiency; increased range	AFTI/F-111 [24], Gulfstream III [25]
	Thickness	Increased low-speed/high-speed performance	Adaptive laminar wing [26]
Out-of-plane	Twist	Increased maneuverability; tip stall prevention	Wright Flyer [11], Digital morphing wing [27]
	Dihedral/gull	Increased lateral stability and rolling capacity; increased maximum speed	XB-70, F/A-18 [10,28], Gull-wing morphing aircraft [29]
	Spanwise bending	Increased lateral-directional stability; decreased wing-root bending	Morphing hyper-elliptic cambered span wing [30]

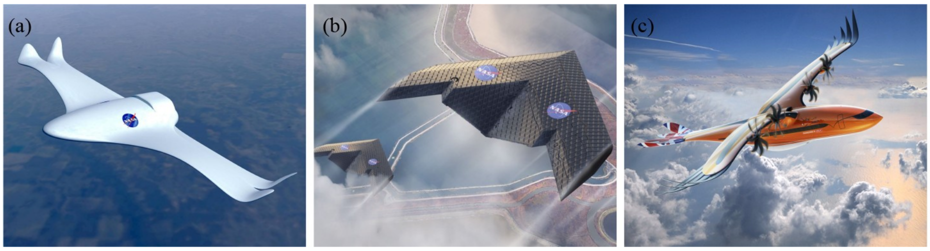

Fig. 2 Conceptual designs of future morphing aircraft: (a) 21st century aerospace vehicle from NASA [45], (b) new kind of airplane wing from MIT and NASA [46], and (c) futuristic conceptual airliner from Airbus [47].

challenging due to extreme service conditions and increasing demands for economy and efficiency. It is typically multidisciplinary because it encompasses cutting-edge research on aerodynamics, mechanical design, structural design, materials science, control system, and optimization [48]. Therefore, providing an overview of existing morphing aircraft designs is meaningful. Given the difficulty of reviewing all relevant studies on morphing aircraft, this paper lists only typical examples, particularly morphing wings on fixed-wing aircraft.

2 Conventional mechanical morphing aircraft

A conventional morphing aircraft changes its configuration during flight by deforming mechanically, and it was primarily introduced by fighters emerging from the arms race during and after World War II [2]. It is the most commonly used morphing mode in military and civil morphing aircraft. This section introduces typical morphing aircraft, but only a few modes are included because it mainly discusses the characteristics of different morphing types and structural morphing forms.

2.1 Variable-span wing structure

The variable-span wing is one of the simplest morphing wings. It combines the advantages of high- and low-aspect-ratio wings in one aircraft, giving the aircraft multipoint optimal performance and multitasking adaptability. However, increasing the span causes the wing–root bending moment to increase and the lift distribution to change, resulting in acid tests for the design rationality and manufacturing quality of the wing [49,50]. Therefore, numerous investigations on span morphing aircraft have been conducted to improve flight performance, roll capacity, and flutter control [18,51,52].

MAK-10, which was designed by Ivan Makhonine and first flew successfully in 1931, was the earliest well-known span-morphing aircraft. Its telescopic wings and pneumatic actuators extended the span to up to 62% (from 13 to 21 m). However, early span-morphing techniques were not adopted due to their bulky mechanisms, and in recent years, span morphing has been designed mainly for unmanned aerial vehicles (UAVs). For instance, Tarabi et al. [53] developed a span-morphing wing model that consisted of a fixed-wing segment and a moving part inside it. Wind tunnel experiments showed that the model reduces drag and improves aerodynamic efficiency, resulting in a 5% increase in flight range and a 17% increase in endurance.

Numerous similar designs with rigid sliding skins have been proposed and tested, but they encountered the same step and discontinuity problems at wing section transitions. To address these problems, Woods and Friswell [54] explored the adaptive aspect ratio wing, an integral span-morphing wing concept with compliant skin made of elastomeric matrix composites (EMCs). The wing can smoothly complete the span-morphing process due to the flexible skin covering the wing mechanism. Similarly, Ajaj et al. [55] designed the gear driven autonomous twin spar for mini UAVs that allows the wing structure to slide from the interior space of the opposite wing during span morphing, thus maximizing space utilization. A wind tunnel test on a physical prototype covered in flexible latex skin demonstrated an increase in the aerodynamic efficiency of the UAV.

Currently, only a few manned span-morphing aircraft are available because of structural weight reduction and continuous sealing of the flexible skin, which limit engineering applications. Moreover, a fast span morphing process can enhance aeroelastic performance, but it also complicates the mechanism [56], and the extra weight subtracts the predicted aerodynamic benefits [57]. Therefore, nowadays, span morphing is considered in conjunction with chord morphing, thickness morphing, and sweep morphing, resulting in multi-mode flight performance enhancement.

2.2 Variable-sweep wing structure

The sweep angle of a wing considerably affects its lift performance and aerodynamic efficiency. Wings with large swept-back angles are good at lifting and dragging at high speeds, especially at supersonic speeds, due to shock wave resistance, and wings with small swept-back angles are good at lifting at low speeds [58]. Many fighters with variable-sweep wings (or swing wings) were proposed during and after World War II to combine high (for fast cruises and supersonic maneuvers) and low (for takeoffs and landings) speeds.

Bell X-5, the first variable-sweep wing aircraft, flew successfully in 1951. Its morphing mechanism was actuated by a jackscrew assembly, and disc brakes provided three sweeping positions: 20º, 40º, and 60º. However, due to its aerodynamic layout and mechanism flaws, violent stalling and uncontrollable spins occurred, resulting in the cancellation of the subsequent research [13,22].

The two most famous variable-sweep aircraft in America are F-111 and F-14. As the world's first mass-produced, practical, variable-sweep aircraft, F-111 can sweep from 16º to 72.5º and fly over Mach 2, as shown in Fig. 3(a) [24]. The wing pivots used for sweeping back and transferring the load to the fuselage have serious fatigue problems, and they create significant trim drag at hypersonic speeds. Through aerodynamic control, F-14's wing sweep angle can range from 20º to 68º, giving it an optimal L/D. Additionally, F-14 can sweep its wings asymmetrically to fly and land in emergencies [59], as shown in Fig. 3(b) [60].

The sweep morphing technologies of this period were also applied to Panavia Tornado fighters, MiG-23 fighters, and Tupolev-22 (Blackjack) supersonic bombers. A sweep morphing airliner, the Boeing B2707, was even considered; it was proposed during the race for commercial supersonic travel in the 1960s and 1970s [61]. At present, variable-sweep technology is the most successful morphing technology applied to manned aircraft. However, due to drawbacks, such as complex mechanism (Fig. 4) [62,63], poor reliability, and large weight, early variable-sweep technologies were withdrawn from the aviation stage and have been gradually replaced by double-delta wings, canard wings, strake wings, and blended wing–body [64]. Recent research on sweep morphing has focused on multi-mode morphing UAVs, which are introduced in Subsection 3.3.

2.3 Other morphing types

As rigid flaps and ailerons gradually replaced flexible wings, mission adaptive wings (MAWs) were introduced in the mid-1980s to improve flight performance by flexibly deforming the airfoil. The U.S. Air Force Research Laboratory and Boeing co-sponsored the Advanced Fighter Technology Integration program, and the MAW system was installed and tested by NASA on an F-111 aircraft. The MAW system used hydraulic motors as morphing actuators, dual redundant computers as flap position controllers, flexible fiberglass as upper surface skins, and sliding panels as lower surface skins. Variable-camber leading-edge and trailing-edge flaps were built and enabled smooth, continuous camber morphing and flap deformation between approximately 1º up and approximately 20º down [65], as shown in Fig. 5 [24]. Flight tests confirmed that MAW improves wing air

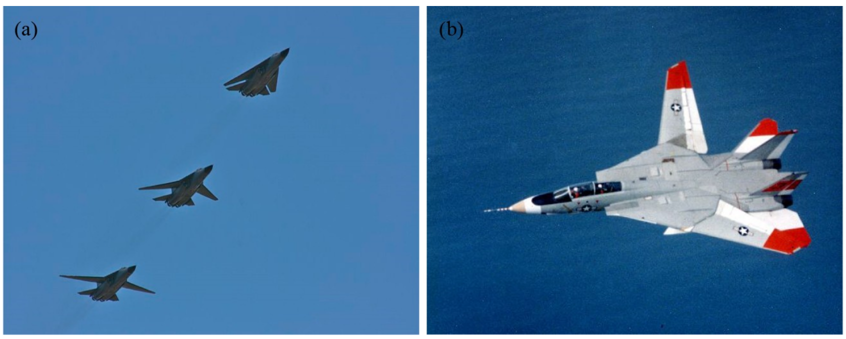

Fig. 3 Sweep morphing process of aircraft: (a) sweeping sequence of F-111 [24] and (b) asymmetrical sweeping of F-14 [60].

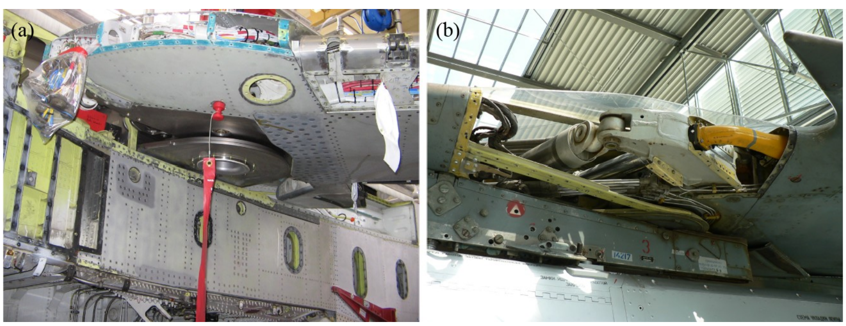

Fig. 4 Complex mechanism of variable-sweep wings [62]: (a) Panavia Tornado and (b) MiG-23 [63].

load by 15% at the constant bending moment and increases range and aerodynamic efficiency by 20%, in line with the expected performance improvements [66].

In recent years, commercial aircraft have begun experimenting with camber-morphing designs due to advances in materials and manufacturing engineering. Working with NASA and the U.S. Air Force, FlexSys Inc. developed a program called Adaptive Compliant Trailing Edge (ACTE). The FlexFoil™ variable-geometry control surfaces of the trailing edge enabled the flaps on the test platform (a Gulfstream III Business Jet) to achieve seamless camber morphing. Compliant fairings were assembled between the wings' morphing segment and fixed segment to achieve a smooth transition that could reduce noise. The flight test results revealed the large-angle camber morphing and high-speed spanwise twist of FlexFoil™ ACTE technology as well as its structural feasibility, structural robustness, aerodynamic performance, morphing stability, and flow separation characteristics [25], as shown in Fig. 6(a) [67]. In 2016, FlexSys Inc. and Aviation Partners Inc. unveiled a new FlexFoil™ morphing technology demonstrator wing, as shown in Fig. 6(b) [68]. This new demonstrator wing features four active control surfaces that can morph smoothly to reduce drag, control load, and improve lift distribution. The four control surfaces also allow for roll control, leading-edge droop, and de-icing because of the new technology [68].

Dihedral morphing wings improve stability and lift by folding a part or all of themselves during flight. The most popular example is the XB-70 supersonic bomber called the Valkyrie. In the late 1950s and early 1960s, XB-70 successfully flew at Mach 3 speeds and in an extremely high-temperature environment, with the outer panels of its wings folding downward by nearly 30º during flight, as shown in Fig. 7 [69]. The downward-folding wings could increase lift by up to 30% without adding additional drag by capturing the shock waves generated by the aircraft, resulting in a considerable enhancement in L/D and directional stability. A wide-Mach-number flight with consistently high flight performance was achieved due to the use of a complex power hinge system. The actuators consisted of a couple of Vickers hydraulic motors located inside the fuselage, a main pump, and a backup pump on each wingtip mechanism. The actuators and power hinges of XB-70 were covered in magnesium thorium fairings, resulting in the use of several tons of materials, which limited its performance [70].

As a typical dihedral morphing wing, winglet bending is often discussed separately because of its unique function of alleviating gust loads. However, the winglet bending technologies that have been used on aircraft are mainly ground foldings that can bypass dimensional requirements and reduce transportation space. Examples include Boeing 777X (Fig. 8(a)) [71], EA-18G (Fig. 8(b)) [72], and Su-33. NASA's Prototype-technology Evaluation Research Aircraft (PTERA), which first flew in 2018, is the latest winglet-bending aircraft, and its details are discussed in Subsection 4.1.

Other morphing aircraft have fuselages and engines that reflect their morphing technologies. Concorde, a supersonic airliner, has a droop-able nose that is typical of fuselage morphing aircraft. Concorde's long-pointed nose is designed to reduce drag and extend forward in

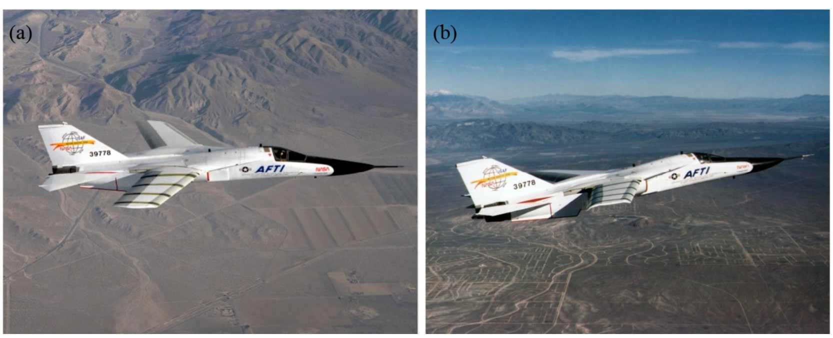

Fig. 5 F-111 aircraft in flight with camber morphing [24]: (a) before morphing and (b) after morphing.

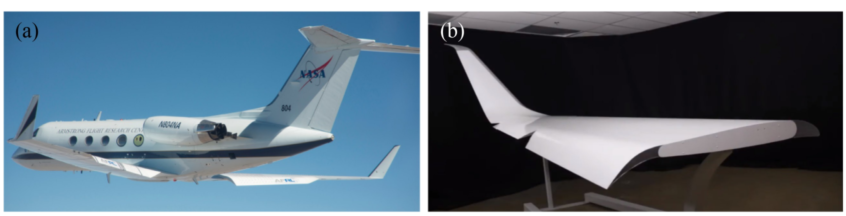

Fig. 6 Camber morphing on (a) the commercial aircraft Gulfstream III [67] and (b) morphing technology demonstrator wing of FlexFoil™ [68].

front of the cockpit to achieve supersonic flight (up to Mach 2). However, due to the high angle of attack during takeoff or landing, the pilot's visibility is obstructed. The nose can morph 5º down for takeoff and 12.5º down for landing to avoid this obstruction, as shown in Fig. 9(a) [10]. The distinguished tiltrotor, V22 Osprey, is a characteristic engine-morphing aircraft. The morphing engine configuration, by changing its thrust direction, endows the aircraft the vertical take-off and landing capability of helicopters and the high-speed cruise capability of fixed-wing propeller aircraft, as shown in Fig. 9(b) [10].

3 Novel morphing structures and technologies for UAVs

In the 1960s, UAVs began carrying sophisticated equipment for military reconnaissance, leading to the rapid development of UAV technology. At present, the technology's market value amounting to tens of billions of dollars has attracted many capital and research units, through which UAVs, especially fixed-wing UAVs, have gradually expanded their mission range, such as monitoring, protection, search, rescue, survey, and defense-related missions [73]. In recent decades, many novel morphing structures and technologies have been constantly tested on UAVs because of their low risk, convenience, and manageable fabrication and cost requirements.

Fig. 7 Dihedral morphing wings of the XB-70 [69].

3.1 Additively manufactured structure

Unlike traditional subtractive manufacturing methods, AM refers to a disruptive manufacturing process that joins materials layer by layer to create an object based on 3D model data (also known as 3D printing). Thus, AM can reduce consumption, increase performance, and improve structural efficiency by using high-strength-to-weight materials and producing lightweight structures [74,75]. The weight, stiffness, and aerodynamic performance of 3D-printed morphing structures have been evaluated, and the results show that AM can manufacture components for morphing aircraft rapidly and cost-effectively; these morphing components have potential aerodynamic benefits [76]. Notably, AM enables the rapid fabrication of ultralight or complex structures, such as topologically optimized structures, lattice structures, and bionic structures, which are widely used in morphing aircraft design but are difficult or even impossible to fabricate through traditional manufacturing methods [77,78]. Polytechnic University of Milan [79] designed and manufactured a wing model with morphing leading and trailing edges, both of which were compliant and

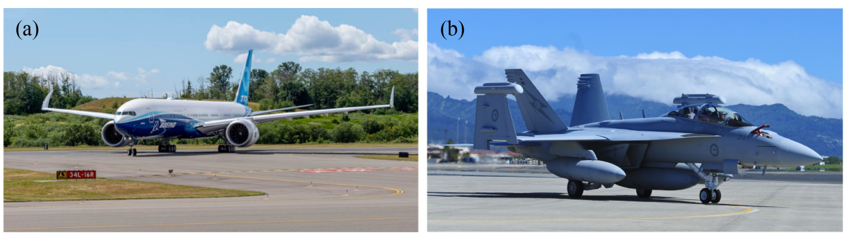

Fig. 8 Folding winglets: (a) Boeing 777X [71] and (b) EA-18G [72].

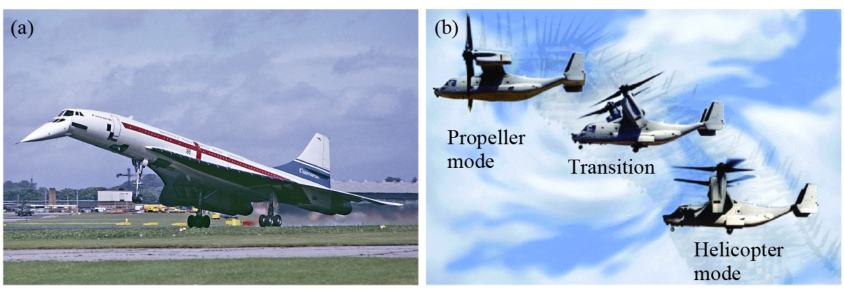

Fig. 9 Morphing fuselage and engine [10]: (a) Concorde and (b) V22 Osprey. Reproduced with permission from Ref. [10] from SPIE.

flexible structures optimized topologically by the genetic algorithm. Stereolithography (SLA) and selective laser sintering were used to fabricate the topologically optimized wing models, which proved to be compliant and elastic. Likewise, researchers have explored the feasibility of using 3D-printed bionic structures, such as imitation fish bone wings, in morphing aircraft [80,81].

In 2020, for the first time, Fasel et al. [82] from ETH Zurich fabricated complete-composite primary and morphing structures of a fixed-wing UAV by using AM technology, and flight tests demonstrated the effectiveness of combining flexible morphing technology with composite AM technology. These morphing structures were reflected in camber-morphing compliant ribs made of 3D-printed continuous fiber composites, namely, carbon fiber-reinforced plastic and polyamide-12. The 3D printing process is shown in Fig. 10(a) [82]. The trailing edge of the main wing achieved a maximum deflection variation of 48 mm through eight actuators, as shown in Fig. 10(b) [82]. The 3D-printed morphing structures proved to be reliable and operable during the flight test. This research demonstrated the possibility of fully automating the manufacturing of UAVs in combination with AM technology.

A crucial direction for the further application of AM in morphing aircraft is 4D printing. The 4D printing process enables structures to deform over time, so it is an extension of 3D printing where time serves as the fourth dimension [83]. Printed fibers can be combined with smart materials that can deform automatically in response to external stimuli to form printed active composites, which have high design freedom and can morph in various ways, such as bending, twisting, elongation, and corrugation [84]. Thus, morphing aircraft with structures produced via 4D printing technology, which have an integrated material–structure–function design, have the potential to actively change their aerodynamic shapes to adapt to changes in the external environment [85]. Many 4D-printed self-morphing structures and actuators have been fabricated and shown to be highly deformable through testing, indicating their feasibility for use in morphing aircraft. For example, to produce composites with embedded continuous fibers, Wang et al. [86] developed a new 4D printing technology through which bilayer structures can achieve programmable deformation with temperature responsiveness. These bilayer structures with multiple deformation patterns and self-repairing capabilities are suitable for smart skins on morphing aircraft. Hoa et al. [87] proposed a novel 4D printing concept for manufacturing an ACTE with a composite corrugated core without a mold, namely, the laminae automatically change to a corrugated shape upon curing and cooling to room temperature. Tests showed that this 4D-printed morphing structure can meet the load requirements of small UAVs.

At present, 4D printing technology still needs major improvements in durability, response speed, control accuracy, mass manufacturing costs, and other areas, but it has great potential for improving future aircraft functionality and efficiency.

3.2 Lattice structure

Precise lattice structures, especially complex 3D lattice structures, can now be manufactured through AM technology. Lattice structures exhibit various properties depending on the material selection and configuration design. The porous configuration leads to the use of minimal materials and an ultralow structure weight, resulting in high specific stiffness and specific strength [88]. The honeycomb configuration allows the structure to achieve large strains at zero or negative Poisson's ratios, resulting in excellent energy absorption characteristics [89,90]. The cubic-type lattice configuration exhibits different deformation modes (stretching, bending, and twisting) and load-bearing properties depending on the type of unit cell and porosity. For instance, with regard to deformation modes, the deformation of F2CC,Z lattice structures is dominated by stretching, whereas that of hollow spherical lattice structures is dominated by bending [91]. Additionally, sandwich structures with corrugated cores have high load-bearing capacities under a flat-faced indenter [92]. Given these properties, lattice structures are widely used in many fields and can be employed as morphing structures.

Lattice structures can be used in morphing aircraft as structural components for load bearing and force transfer or as functional components for morphing. When lattice

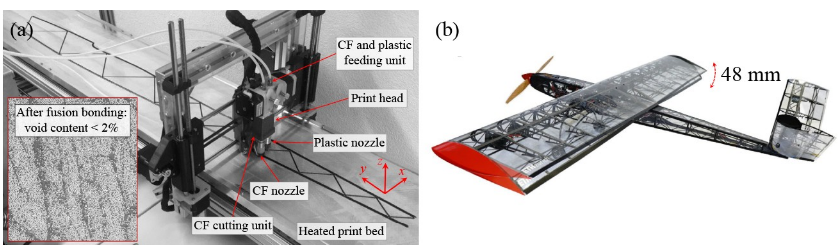

Fig. 10 Morphing unmanned aerial vehicle by additive manufacturing of composites [82]. (a) Fuselage truss structure undergoing 3D printing and (b) morphing actuation process and maximum deflection change. Reproduced with permission from Ref. [82] from Elsevier.

structures are utilized as morphing components of morphing wings, the small cell scales and large cell numbers considerably reduce the gaps between discrete moving and fixed parts, resulting in a smooth airfoil profile. Vocke et al. [93] designed and fabricated a prototype morphing-wing segment capable of 100% spanwise expansion. It had many V-shaped bending members attached to the wing ribs, such as springs, to enable zero-Poisson morphing of the planar core. The structure was manufactured by SLA technology and covered with a silicone elastomer skin in which unidirectional carbon fibers were embedded to minimize the Poisson effect. Hence, a smooth aerodynamic profile could be maintained during span morphing. In the wind tunnel tests, the prototype completed span morphing at high speeds (maximum speed of 130 km/h), and the maximum recognizable out-of-plane deflection was slightly greater than 0.5 mm.

Although AM technology ensures the structural integrity of lattice structures with integrated molding, subsequent repairs and replacement are inconvenient and uneconomical, and the modular manufacturing capability of these structures is limited. Moreover, AM has limitations when it is used for large lattice structures. Therefore, reversibly assembled cells that can produce lattice structures have been proposed. Cheung and Gershenfeld [94] introduced carbon fiber-reinforced polymer composite cells that could reversibly assemble 3D lattices by integrated mechanical interlocking connections. On this basis, Jenett et al. [27] from MIT described discretely and reversibly assembled digital morphing wings that consisted of modular building block parts and could perform continuous spanwise twist deformation. Through the connection points, the transverse and longitudinal parts transferred twist deformation from the actuator to the whole wing during morphing. As a result of the discrete assembly, manufacturing complexity is reduced because relatively simple modules can be mass produced and joined to form complex structures, as shown in Fig. 11(a) [95]. A flying-wing aircraft is designed by NASA and MIT based on similar principles (Fig. 11(b) [96]). It incorporates a programmable material system into a large-scale, ultralight, and compliant aeroelastic structure. The prototype is largely composed of ortho-octahedral cells, and adaptive aeroelastic shape morphing is achieved. The modularity of the structure allows distributed sensing and computing systems to be integrated easily.

3.3 Multi-mode morphing UAVs

In response to the issues caused by a single morphing form, other complex morphing aircraft, such as ornithopters with bionic morphing structures and multi-mode morphing UAVs that combine two or more morphing models, have been tested in the past two decades.

In 2002, the Defense Advanced Research Projects Agency (DARPA) initiated the MAS program [39]. This program led to the development and successful flight testing of Morphing Flight–vehicle Experimental (MFX-1), a multi-mode morphing UAV that can change span, sweep angle, and wetted area simultaneously. The wings were driven by computer-controlled linear actuators and mechanical four-bar linkages during the flight test. Combined with an elastomeric silicon skin supported by an underlying ribbon structure, the actuators morphed the wings successfully, with the wing area changing by 40%, the wingspan changing by 30%, and the wing sweep varying from 15º to 35º [97,98]. A large morphing UAV, namely, MFX-2, was subsequently tested in 2007, and it had a variable wing area of 40%, a variable span of 73%, and a variable aspect ratio of 177% [13].

Under the MAS program, Lockheed Martin Aeronautics Company presented a double-hinged folding- and flying-wing aircraft concept. It was an unmanned combat air vehicle with two foldable wings that allowed for radical deformation of the span and wetted area, enabling the aircraft to cruise and loiter efficiently over long distances with a large wingspan, fold its wings when necessary to transition to high-speed dash and kill, and morph back after the mission is accomplished. It was a groundbreaking concept, but it brought new design problems, such as wrinkles in the folded position and flexible, seamless skin selection [99,100]. The concept, however, provides a great reference for the design of multi-mission UAVs.

Recently, micro air vehicles (MAVs) have been

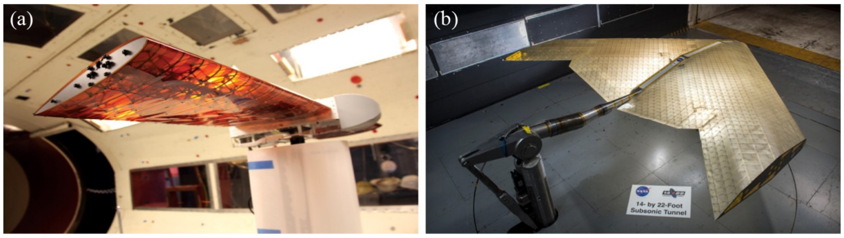

Fig. 11 Morphing wings by reversibly assembled lattice structures: (a) digital morphing wing [95] and (b) elastic shape morphing wing [96].

equipped with a novel bionic morphing wing inspired by the folding mechanism of bird feathers. The wing consists of a fixed inner segment and a folding outer segment with artificial feathers, which allow the sweep angle and wetted area to be changed simultaneously. Di Luca et al. [101] and Hui et al. [102] independently developed similar MAV designs. The former verified the concept's capability to improve low-speed maneuverability, enhance high-speed performance for wind rejection, and roll the MAV by actuating the wings asymmetrically. The latter demonstrated how wingtip structures can be used to improve lateral stability and reduce drag by reducing the strength of the vortex at the wingtip. Ajanic et al. [103] further developed this concept by morphing the tail. The outer wing segments of this UAV, which was code-named LisHawk, are swept forward during cruise to improve maneuverability, and the tail is deployed to provide additional lift and drag (Fig. 12(a) [103]). If aggressive flight is required, it can sweep the wing segments backward and retract the tail, thus improving longitudinal stability and minimizing power consumption (Fig. 12(b) [103]). The flight test demonstrated its complete and efficient deformation process (Fig. 12(c) [103]).

Chang et al. [104] developed a biohybrid UAV in 2020 with 40 underactuated pigeon remiges, which make this design different from previous ones. However, the researchers' purpose was to study how the directional fastening of feathers and passive feather redistribution by connective tissue affect feather coordination in birds' flight. The related results were published almost simultaneously in *Science* [105].

The focus of research on morphing aircraft has shifted from manned aircraft to unmanned aircraft. Conventional morphing aircraft mostly use steering engines, hydraulic systems, linkages, hinges, and other deformation mechanisms to complete the morphing process. Through development, the form of morphing has changed from flexible to rigid and then back to flexible again, and advances in aerodynamics and UAV technology have played a major role in this transformation. The conventional morphing form has no advantages in terms of weight and complexity when compared with the smart materials and structures developed on a large scale at the end of the last century, but its stability, accuracy, and existing sufficient research base make it one of the main morphing modes at present. Conventional morphing aircraft still have bright prospects due to advances in manufacturing technology.

4 Future morphing aircraft

The majority of morphing aircraft at present are passive morphing aircraft, that is, the pilot gives instructions or performs a series of operations to complete the morphing process. With the development of smart technologies, researchers are exploring active morphing aircraft that can autonomously change their wings, tails, and fuselage to maintain optimal flight performance regardless of changes in the external flight environment. This design concept has two options.

(a) Equip existing morphing aircraft with advanced and sensitive sensors. As a result of this option, the sensitivity and accuracy of the control system can be improved, but the complexity of the circuit system will also increase, resulting in additional weight. However, this option has the distinct advantage of leveraging the maturity of existing morphing technology.

(b) Apply smart materials and smart structures driven by such materials to morphing aircraft. Smart materials respond to external stimuli (e.g., light, electricity, heat, and force) by deforming into a specified shape, so they can perform sensing, actuating, and load-bearing functions simultaneously. As a result, morphing aircraft can reduce their weight and complexity considerably. This option poses the challenge of reconciling the structural stiffness required for bearing and the structural flexibility required for morphing.

In this section, we discuss smart material-driven morphing aircraft and the challenges to be overcome in future morphing aircraft designs.

4.1 Morphing aircraft driven by smart materials

Although SMA, shape memory polymers (SMPs), and macro-fiber composites (MFCs) are already used in morphing aircraft, many of their properties are yet to be

Fig. 12 LisHawk drone [103]. (a) Aggressive fight attitude, (b) cruise flight attitude, and (c) transformation of the morphing wing between cruise and aggressive flight during testing.

investigated for stable and controlled applications. Nevertheless, related research has been ongoing, and two typical smart material actuators are discussed here.

4.1.1 SMA actuators

SMA was discovered nearly a hundred years ago. In 1932, the Swedish scientist Ölander observed the phenomenon of martensite elongation with temperature in Au–Cd alloys. More than 30 years later, Buehler et al. of the U.S. Naval Ordnance Laboratory discovered the “memory” behavior of Ni–Ti alloys, that is, when the temperature rises to a particular transition value, the deformed alloy returns to its original shape [106]. Such deformation behavior is called the shape memory effect (SME), and alloys with SME are called SMA. SME exhibits considerable shape recovery (in the order of 8%), and SMA can apply activation energy (energy density of up to 10^7 J/m^3) in the form of recovery stress (up to several hundred MPa) during this period [107]. Given their corrosion resistance, biocompatibility, superelasticity, and two-way SME, SMA actuators have gradually entered the engineering application phase and are now used in aerospace, automotive, bridge construction, biomedicine, and other fields.

SMA actuators can be classified into three categories on the basis of their deformation form: linear, twisting, and bending actuators. Linear actuators are the earliest and most common actuators used in morphing aircraft because of the relatively large strain and stress created by the contraction of SMA wires. As early as 1995, in Phase 1 of the Smart Wing Program of DARPA, Air Force Research Laboratory, NASA, and Northrop Grumman, SMA wire actuators were used to drive hinge-less control surfaces, namely, a flap and an aileron [108]. At present, SMA-based linear actuators are still being designed for different morphing modes of aircraft. For instance, Brailovski et al. [109] designed a variable-thickness morphing wing driven by SMA wires and bias springs. Rodrigue et al. [110] designed a twist morphing wing driven by crosswise SMA wires arranged from top to bottom. Emiliavaca et al. [111] designed a camber morphing wing driven by SMA microspring actuators arranged in sections inside the wing. Meanwhile, a new integrated layout and topology optimization design for the morphing wing that innovatively combines SMA actuators and topology optimization techniques was presented by Zhu’s group from Northwestern Polytechnical University (NWPU) [112]. This design can simultaneously optimize the topology of wing substrates and the layout of SMA wire actuators. The team also designed a flexible morphing wing structure that combines bionics, lattices, and AM technology, as shown in Fig. 13(a). This design features a fishbone-like wing rib structure with linearly driven SMA wires for bidirectional deformation. With the distributed actuator arrangement, the wing can perform synchronous, bird-wing, and U-shaped morphing, as shown in Figs. 13(b) and 13(c). Flight tests demonstrated the flight feasibility of this servo-less, flexible morphing wing.

Twisting actuators were also investigated in Phase 1 of the Smart Wing Program. The aim was to achieve actively variable wing twists with SMA torque tubes [113]. NASA and Boeing jointly developed Variable Camber Continuous Trailing Edge Flap (VCCTEF), which is a multisegment flap design with 15 individual flap elements and flexible skins. Continuous flap deformation allowed the aircraft to adjust the twist angle and bend of the wing in response to changing cruise conditions, thereby optimizing the wing’s performance. Among the hydraulic, electric, and SMA torque rod actuators evaluated, the SMA actuators were found to have the best weight advantage due to their ability to bear loads and actuate structures simultaneously without conventional flap tracks. VCCTEF has also been found to reduce drag by up to 6.31% and improve L/D by up to 4.85% via wind tunnel experiments [114]. NASA, Boeing, and Area I, Inc., collaborated on the Spanwise Adaptive Wing (SAW) Project, which was the first completely integrated flight testing that utilized high-

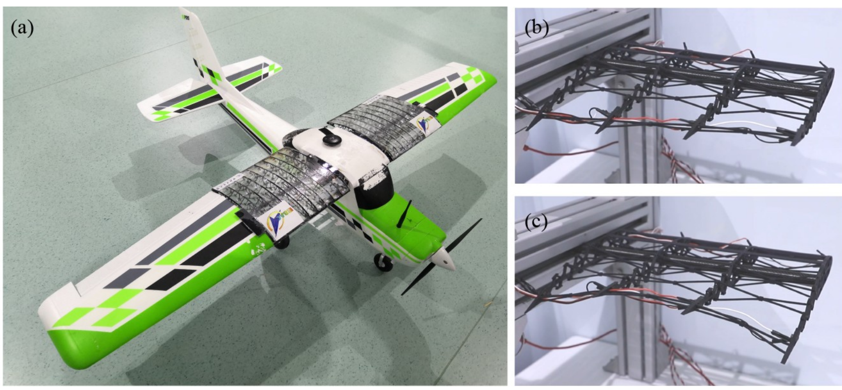

Fig. 13 Flexible morphing wings driven by shape memory alloy wires actuators: (a) morphing wings assembled on an experimental aircraft, (b) bird-wing morphing, and (c) U-shape morphing.

temperature SMAs with flight-related characteristics. A precipitation-strengthened NiTi-20Hf SMA tube was used as a twisting actuator of a morphing winglet, and it had a design output torque of 56 N·m and an angular displacement of 90º. The details of the actuation systems are shown in Figs. 14(a)–14(c) [115]. In 2018, SAW was installed on the PTERA subscale testbed. The total weight of the system was 80% lower than that of the conventional system due to the use of SMA actuators, and the former system had a simpler layout and easier assembly than the latter. During the flight, the PTERA winglet completed an up-and-down deflection from 0º to 70º, as shown in Fig. 14(d) [116].

Although bending SMA actuators are relatively rare, they still have a well-known application, namely, Boeing's variable-geometry chevrons (VGCs). They change the shape of these chevrons to minimize noise by laminating bendable SMA sheets to the structure surface. Full-scale flight testing has been conducted on a 777-300ER equipped with GE-115B engines [117]. Inspired by this testing, Boeing designed and tested a variable-area jet nozzle that can change the area by 20% to obtain a considerable decrease in fuel consumption and noise [118]. Unlike most current SMA actuators that require additional heat or power to heat the SMA, this type of actuator can achieve an entirely autonomous operation on the basis of ambient temperature changes from take-off to cruise, demonstrating a true active morphing aircraft.

SMA is not widely used in structure actuation of morphing aircraft due to its nonlinear hysteresis behavior and relatively low actuation rates. For further development, accurate constitutive models that can predict the deformation and fatigue behaviors of SMA are required to provide guidance for engineering applications and a solution to the heat transfer limitation (long time required to heat/cool the SMA, particularly for large parts).

4.1.2 MFC actuators

Piezoelectric material actuators have many advantages, including high energy density, high energy conversion

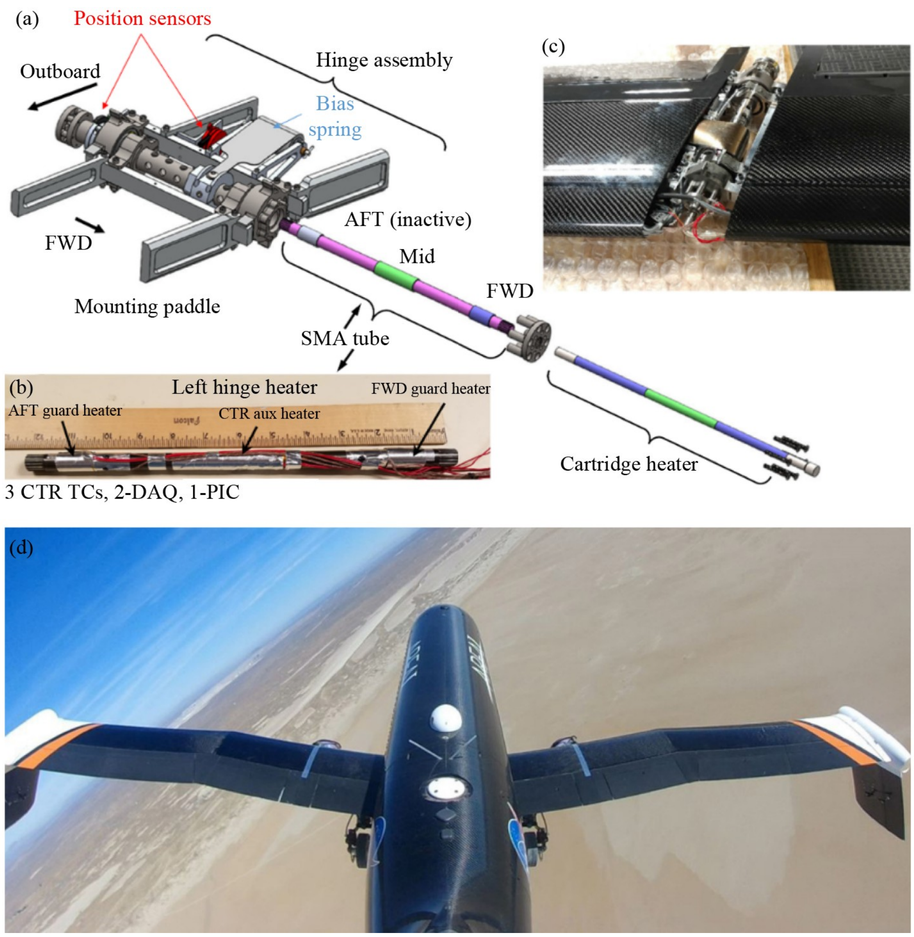

Fig. 14 Spanwise Adaptive Wing Project [115,116]. (a) Exploded view of the actuator, (b) SMA tube with thermocouples and guard heaters, (c) SMA actuator assembly for the prototype-technology evaluation research aircraft wing, and (d) prototype-technology evaluation research aircraft during the flight test. SMA: shape memory alloy. Reproduced with permission from Ref. [115] from Springer Nature.

rate, wide operating frequency range, and high control accuracy, when they are used in structure morphing control. For example, in Phase 2 of the Smart Wing Program, piezohydraulic pumps and piezoelectric ultrasonic motors were tested to control wing trailing edges [119]. However, traditional piezoelectric materials, such as piezoelectric ceramics, have brittleness, large weight, low durability, and small strain, which limit their wide application in operating environments requiring large morphing scales. The MFC piezoceramic configuration can overcome this issue because of its flexibility and robustness. MFC includes rectangular piezoelectric ceramics covered on both sides with adhesive films containing tiny electrodes, which transfer the voltage directly to/from extremely thin ribbon-shaped rods [120]. The lightweight, thin, and lamellar actuators manufactured by MFC are widely used in many aerospace applications for sensing and low-power actuation, especially for bending actuators that offer large structural deflections.

MFC actuators are mainly used in variable-camber aircraft. Bilgen et al. [121] explored the application of MFC in MAV; they used two MFC patches in elevators/ailerons (elevons) to accomplish pitch and roll actuation by morphing the wings' camber symmetrically and asymmetrically. Compared with wings with conventional control surfaces, MFC-actuated composite wings exhibit continuous camber morphing during flight and wind tunnel testing, leading to a reduction in drag and moment of inertia. This reduction, in turn, results in expanded actuation bandwidth and increased efficiency. Similarly, Prazenica et al. [122] used MFC actuators to drive ailerons and achieve roll actuation on a medium-scale, fixed-wing UAV. Debiasi et al. [123–126] from Temasek Laboratories of the National University of Singapore conducted a series of studies, in which they designed and tested MFC-actuated multi-mode morphing wings. Paper-thin titanium sheets, carbon-fiber sheets, and materials were utilized as the wings' upper/lower skins, and MFC actuators were bonded to the inner side by vacuum bags. At the leading or trailing edge of the wing, thin pockets were arranged to allow the skin to slide inside. Positive or negative voltages could cause the skin to morph inward or outward in the longitudinal direction. Thus, the wing demonstrated multiple morphing modes, including thickness and camber morphing, in addition to skin sliding. Wind tunnel tests demonstrated that the wing model simultaneously increases lift and reduces drag, and its dynamic morphing delays the onset of stall.

MFC actuators have also been used in morphing winglets. Chen et al. [127] from Xi'an Jiaotong University proposed a groundbreaking design where a hinge is equipped to transform the bending deformation of the MFC actuators into the rotation of the winglet structures so that the adaptive cant angle can be achieved. A series of experiments demonstrated that the MFC bending actuator has excellent bending performance and load resistance, and the morphing winglet shows excellent flexibility. MFC actuators have also been applied to ornithopters [128,129].

Although the driving efficiency of MFC actuators is better than that of SMA actuators, nonlinear behaviors, such as hysteresis and creep, are still serious drawbacks [125]. Additionally, how to suppress vibrations during the morphing process and how to improve strain output stability remain unexplored.

Other smart materials, such as SMP, dielectric elastomers (DEs), and magnetostrictive materials, are used as actuators on morphing aircraft. Typical applications are listed in Table 2 [108–110,114,116–118,123,127,130–134], but only some of the applications are listed due to the wide variety.

To date, smart material actuators are incorporated into almost every part of morphing aircraft, and these actuators can drive the aircraft through various morphing modes. The majority of smart material applications, however, rely on human control commands to initiate deformation and actuation processes, rather than on their own judgment based on the external environment. This situation means that smart materials' unique sensing

Table 2 Smart material actuators on morphing aircraft

Smart material type	Actuator form	Application scenario	Example
SMA	Linear	Contract linearly to drive the deflection of the mechanism or structure, thus completing the morphing process	Smart Wing Program, 1995 [108]; variable-thickness wing, 2010 [109]; twist morphing wing, 2016 [110]
	Twisting	SMA torque tubes drive aileron deflection or winglet rotation	VCCTEF, 2014 [114]; PTERA, 2018 [116]
	Bending	SMA sheets are attached to the structures to drive engine jet nozzle morphing	VGC, 2007 [117]; variable-area jet nozzle, 2008 [118]
MFC	Bending	Fix inside or outside the skins, morph the airfoil by bending the skins, or drive the mechanism to deflect the wing	Multi-mode morphing wings, 2013 [123]; adaptive winglet, 2022 [127]
SMP	Curling	Skin and filler together to curl or deploy the wing	Deployable wing, 2009 [130]
	Expansion	Filler expansion achieves chord length increase and thickness decrease	Chord morphing wing, 2004 [131]
DE	Expansion	Unidirectional expansion bends the wing in the other direction	Foldable elevon, 2014 [132]; flexible morphing wing, 2019 [133]
Magnetostrictive material	Linear	Magnetostrictive pump drives span morphing	Span morphing wing, 2007 [134]

capabilities are not fully utilized. Therefore, smart materials, intelligent control strategies, and other advanced morphing drive systems need to be explored to achieve a true active morphing aircraft with self-sensing, self-adapting, and even self-repairing capabilities.

4.2 Challenges for future morphing aircraft

Many problems still need to be solved before future active morphing aircraft can be built. These problems include accurate and stable control systems, efficient actuation systems, and flexible structures or skins that can simultaneously meet the requirements of small weight, high load capacity, and large deformation.

4.2.1 Flexible structure

The primary function of the aircraft structure is to provide and maintain the desired deflection when enduring external aerodynamic loads, but morphing aircraft structures are expected to exhibit sufficient, even dramatic, shape changes when morphing to fit the current flight condition. Herein lies the paradox: a small deflection implies high stiffness to maintain the shape and carry the load, but a large deformation implies low stiffness to achieve shape change. Thus, a major challenge for future morphing structures is to maintain balance between rigidity and flexibility.

Fishbone-like bionic structures provide a solution. Woods and Friswell [80] from Swansea University built a prototype of the fish bone active-camber morphing concept. The prototype structure consisted of a thin, chordwise, bendable spine and a plurality of stringers for fixing and supporting the pretensioned EMC skin. Although flexible trailing edge morphing and external load resistance can only be achieved through antagonistic tendon drive systems, the fishbone structure demonstrated the possibility of using flexible structure designs. The multi-mode morphing-wing structures designed by Zhu et al. from NWPU, which are shown in Subsection 4.1.1, also adopt a fishbone imitation design for wing rib structures. Unlike Woods and Friswell [80], Zhu et al. used SMA wires with a diameter of only 0.3 mm as the actuators. The antagonistic actuator layout allowed the wing rib structure to deform in both directions while reducing weight, as shown in Fig. 15. Similar structures can be found in Refs. [81,135]. Lattice and corrugated structures can also accomplish flexible deformation. The former is deformed by flexible cells or connection structures between cells; the latter is deformed by the expansion and contraction of the corrugated part, and the load is carried by the other components. Furthermore, the load-bearing components can be optimized to some extent, as attempted by Molinari et al. [136,137], to achieve low weight.

In all of these structures, a high-energy actuation system is required to drive the structure and maintain its position after morphing. To avoid this requirement, Nicassio et al. [138] proposed a passive, low-energy, and morphing-surface concept that consisted of a bistable composite plate with a customizable activation force, the magnitude of which was determined by the pressure difference between the upper and lower airfoil cambers of the aircraft wings. This work demonstrated the potential of using bistable structures despite the increased requirements on their constraints, lay-ups, and aspect ratios.

Materials, such as those used for AM or composite construction, need to be considered in addition to the complexity of the design and the diversity of the requirements for flexible structures. Achieving balance between deformation and load bearing is another major challenge in selecting skin materials for flexible structures.

4.2.2 Flexible skin

A wing (either rigid or flexible) can be divided into two parts during the morphing process: the fixed section and the deformed section. Thus, the transition section is a

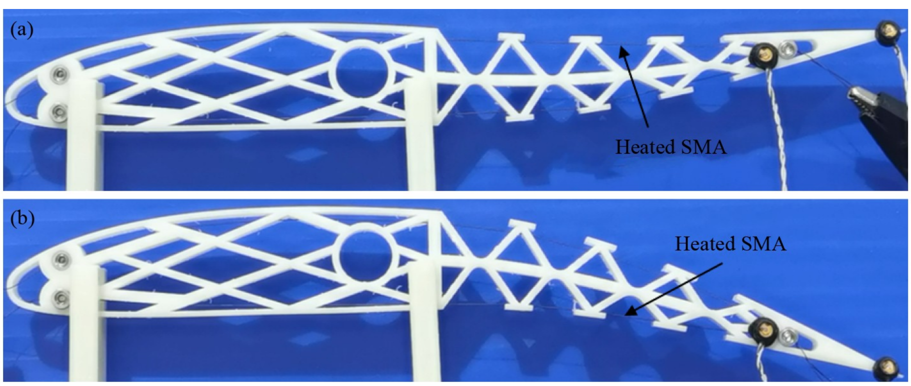

Fig. 15 Fishbone-like wing rib structure from Northwestern Polytechnical University: (a) upward morphing and (b) downward morphing. SMA: shape memory alloy.

concern. For conventional fixed-wing aircraft, rigid skins are laminated to the fixed and deformed sections, and the transition section exists in the form of gaps, which cause premature flow separation and loss of aerodynamic efficiency and increase the overall noise of the aircraft [139]. A flexible skin is needed to cover the gaps or flexible structures and thus eliminate this drawback, but the issue is how to find a skin material that can bear external aerodynamic loads while achieving seamless and flexible deformation.

In response to the need for noise control in airplanes, especially passenger airplanes, the German Aerospace Center has been working in close cooperation with Technical University Munich on the FlexMat Project [140], in which a transition skin concept is presented. This skin connects a morphing leading edge and an aileron with the fixed-wing part, thereby eliminating all the gaps and steps. As a typical EMC, the skin substrate is made of ethylene–propylene–diene monomer rubber, and the leading and trailing edge parts are mixed with glass and carbon fibers, respectively. The fibers are arranged in the form of strips in the chordwise direction to enhance the stiffness of the skin, so the flexibility of the rubbers and the rigidity of the fibers are combined to obtain a smooth transition contour.

The buckling of the contracted section during wing morphing is a serious problem for the flexible skin covering of flexible structures. A common solution is to set the slip joint, namely, allow a tongue to slide inside the wing's fixed part. However, a step still exists in the slip joint mechanism, and local thickness changes during deflection create other drawbacks [81]. Another possible solution is to pretension the skin when it is applied to cover the entire wing's morphing part so that when the structure contracts, the skin regains its original shape. Thus, no wrinkles appear, and out-of-plane stiffness is increased. Silicone or rubber is recommended for this type of application [80,141]. To eliminate buckling, Pennsylvania State University designed a novel flexible skin [142] that consisted of a flexible honeycomb structure with compliant face sheets having low in-plane stiffness, high strain capability, and high out-of-plane stiffness. The experiment showed that the skin has better deformation adaptability than silicone skin, and other skin structures similar to it have been investigated recently [143,144].

Variable-stiffness materials, such as SMP, are ideal materials for flexible skins because skin stiffness changes during load-bearing or deformation tasks. When the temperature decreases and increases, the vitrification phenomenon appears and disappears in SMP, thereby increasing and decreasing the stiffness, respectively. Sun et al. [145] from the Harbin Institute of Technology manufactured, simulated, and tested SMP skin, which demonstrated the ability to withstand air loads and alter its shape under low loads. Moreover, as a smart material, SMP skin can be used to create smart skin that changes shape actively. Flexible, smart sensing skin that integrates high-quality sensors and flexible skin materials has also been discussed in recent years [146].

4.2.3 Other challenges

The control system needs to be upgraded before it can be applied further in morphing aircraft. A highly accurate control system should be used to stabilize the aircraft's attitude when performing morphing processes, especially those on a large scale, such as span and sweep morphing. For example, Shao et al. [147–149] from NWPU conducted a series of longitudinal dynamic control studies on a wing-folding UAV. The UAV they used had an internal rotatable wing and an external wing that remained horizontal while the internal wing rotated. They found that the lift and pitch attitude vary as a result of the dramatic changes in wingspan, area, and inertia tensor during the morphing process. The UAV linear parameter-varying model was created using Jacobian linearization, and pitch-axis attitude control was designed for the entire morphing process to maintain stability and achieve good tracking performance and robustness. Moreover, due to the stability problems and nonlinear characteristics of smart materials, a precise and efficient control system is required to fix the wing in the designated position when smart material actuators, such as the intelligent control system developed by Grigorie et al. [150], are used. This system can be designed based on a fuzzy controller, supported by an on–off controller, and used for SMA actuator control on morphing aircraft.

Morphing system optimization and low weight are also important considerations. Actuator layouts, structure configurations, and even skins can be optimized separately. Hodson et al. [151] applied a biologically inspired aeroelastic topology optimization method on morphing wings in supersonic flow. This method can determine the optimal actuation settings by integrating a gradient-based optimization framework into the design process. Zhu et al. [112,152] presented integrated optimization design methods based on topology optimization techniques and smart material actuators. The two designs differ from others because the actuators assume a load-bearing role, and their layouts are optimized simultaneously. With regard to skin optimization, Dayyani and Friswell [153] optimized the geometric parameters of a skin composed of coated composite corrugated panels, thereby minimizing the in-plane stiffness and weight while maximizing the out-of-plane stiffness. However, experiments still need to be performed to validate existing design schemes, and full commercial application remains unachieved.

5 Conclusions

A vital direction for future aircraft research is the design of morphing aircraft that adjust the structure of the wings, tails, and fuselages to optimize aircraft performance under various flight conditions. Current morphing schemes still have many drawbacks, but researchers continue to update and improve them, and morphing aircraft still have many development and application prospects. In this paper, we elaborate the structure characteristics and applications of traditional and future morphing aircraft, discuss the advantages and disadvantages of various morphing technologies, and forecast the future development of morphing aircraft.

(a) Advanced aerodynamic theory and control system design should be constantly proposed and investigated for foreseeable system-level optimizations and weight reductions. Although numerous morphing aircraft, such as F-14, F-111, and MiG-23, have been replaced, an increasing number of new morphing aircraft applied with new morphing technologies, such as AM and lattice technologies, are being designed to eliminate the shortcomings of previous ones. The continuing progress of morphing technologies is driven by similar technologies.

(b) Testing of morphing technologies based on UAV platforms should continue. The boom in UAV technologies has improved the fault tolerance of morphing technology trials and enabled researchers to finish explorations and validations of new morphing schemes in a relatively short period and at a low cost. For instance, the flexible structure design used on UAVs can be tested immediately after it is presented. Morphing UAVs that can complete compliant and seamless morphing, along with the design and preferential selection of flexible skin materials, still have room for development.

(c) Additional in-depth research on the mechanism, fatigue, and control of smart materials should be conducted to enhance their applications in morphing aircraft. Smart materials, such as SMA, SMP, and piezoelectric materials, are already extensively applied in morphing aircraft, but their actuators still have limitations, such as low actuation efficiency and small actuation displacement. Further improvements in material properties and control capabilities are required to achieve lightweight, high-stress, and large-strain smart actuators. Furthermore, smart materials' sensing properties need to be harnessed to make morphing aircraft truly smart.

Nomenclature

ACTE	Adaptive compliant trailing edge
AM	Additive manufacturing
DARPA	Defense advanced research projects agency
DE	Dielectric elastomer
EMC	Elastomeric matrix composites
L/D	Lift-to-drag ratio
MAS	Morphing aircraft structure
MAV	Micro air vehicle
MAW	Mission adaptive wing
MFC	Macro-fiber composite
NWPU	Northwestern Polytechnical University
PTERA	Prototype-technology evaluation research aircraft
SAW	Spanwise adaptive wing
SLA	Stereolithography
SMA	Shape memory alloy
SME	Shape memory effect
SMP	Shape memory polymer
UAV	Unmanned aerial vehicle
VCCTEF	Variable camber continuous trailing edge flap
VGC	Variable-geometry chevron

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Conflict of Interest The authors declare that they have no conflict of interest.

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