Research Status and Expectation of Intelligent Deformable Wing Aircraft

Liangzheng Ma¹, Wei Huang¹, Yuntu Ao¹, Lin Yi¹,∗ and Ying Wang¹

¹ Air and missile defense college, Air Force Engineering University, Xi'an, China
∗Corresponding author e-mail: 841420273@qq.com

Abstract. The performance requirements for military reconnaissance, military strikes, long-range transport and medical rescue are constantly increasing. The traditional wing has bottlenecks in terms of improving flight efficiency and mission adaptability, which restrict the performance of the aircraft. With the development of new intelligent materials and continuous pursuit of aerodynamic performance, the concept of deformable wing emerges as the times require. This paper analyzes the advantages and disadvantages of deformable wing aircraft, summarizes the research results and current situation at home and abroad, and finally makes a prospect for the development of the technology.

1. Introduction

It is difficult to ensure that the guided ammunition has good maneuverability and control performance in a large range of flight speed envelope in the traditional flight mode with constant wing shape. Under this background, the concept of deformable wing came into being. The lift coefficient of airfoil is obviously affected by different deformation; the lift oscillation phenomenon can be reduced by the appropriate amount of deformation; the increase of deformation can restrain the vortex separation in the process of pitching, and thus delay the deep stall hysteresis effect. At present, domestic and international research on deformable wings is still mainly focused on the single direction of the wing large scale deformation and wing folding deformation. But for the smooth continuous deformation research and multi-dimensional deformation structure design and other aspects of the research is still limited, which need to further study. The existing deformable aircraft can meet the requirements of the changes of backward sweep angle and chord curvature under different conditions. When these deformable wings are deformed in the deformable direction, there is usually a beam, plate, or other structure or locking mechanism in the non-deformable direction to ensure the overall rigidity and load capacity of the wing. However, the single wing deformation type can hardly meet the requirements of wide speed range flight and multi-environmental adaptability of the aircraft. The true deformable wing concept is a seamless integration of new intelligent materials, actuators, exciters New design concepts. It is necessary to carry out research on deformable wings with certain structural stiffness and load-bearing capacity that can achieve multi-dimensional continuous deformation.

In this paper, based on the summary of scholars' research on the deformed wing, the research status of the deformed wing aircraft at home and abroad is summarized. Finally, the development of the deformed wing is prospected on the basis of the structural form and flight principle of the wing.

2. Development history at home and abroad
In the early research, due to the lag of the development of material science, researchers can only control the relative motion of each rigid body of the wing to achieve the deformation of the wing, such as expansion, folding, torsion, bending, etc. So the structure designed is cumbersome and complex, which limits the improvement of the overall performance of the aircraft. With the development and application of smart materials and smart actuators, people have a strong interest in flexible wing, and have carried out extensive research. At the same time of ensuring the smoothness and continuity of the wing shape, the geometric parameters such as wing area, angle of attack, chord length and curvature are changed through flexible deformation, which effectively improves the aerodynamic performance of the aircraft. The airspace and speed domain of future vehicles are expanding, and a fixed aerodynamic shape may not be able to meet the aerodynamic and flight performance requirements of vehicles in different flight conditions. After entering the 1990s, the western developed countries have developed new concept wing design technologies such as active flexible wing technology (AFW) and adaptive wing technology (AWT).

In the 21st century, with the continuous emergence of new space missions, the requirements for inflatable wing aircraft are also increasing, especially in recent years, the most urgent demand for large-scale inflatable wing aircraft. The development of materials and electronic technology in the space age, as well as a deeper understanding of aerodynamics, prompted researchers to start to consider the role of deformable wings in high-performance aircraft.

3. Advantages and disadvantages of deformed wing[1-3]

Advantages of deformed wing:
- Expand flight envelope;
- Replace the traditional control surface to reduce the complexity of the system;
- Improve reliability;
- Adjust the flow field around the aircraft to reduce resistance;
- Reduce vibration and flutter;
- Reduce radar reflector and improve stealth performance;
- Reduce the empty weight of the aircraft and increase the payload;
- Improve the efficiency of fuel and increase the endurance of the aircraft.

Disadvantages of deformed wing:
- Complex design;
- Operational difficulty;
- High failure rate;
- Limited space for the actuators that deploy and retract the wings.
- Adverse effects of structural fatigue and kinematic hysteresis caused by repetitive motion of the wing;
- Adverse effects on the aircraft of the change in aerodynamic centre and the change in the centre of gravity due to deformation;
- New materials are needed to reduce aircraft weight;
- Complex variable wing mechanism limits the improvement of a series of performance of aircraft, such as load, shape, stealth, etc.

4. Research progress of intelligent deformable wing

4.1. Research progress abroad.

According to the existing foreign data, there are two main types of the layout of the deformable aircraft. One is the local deformation with "intelligent" materials; the other is the large-scale deformation with mechanical structure (or mechanical plus intelligent material structure). Local deformation belongs to the field of flow control, such as changing the local airfoil shape or bending degree of the wing to improve the aerodynamic efficiency of the wing. Large scale deformation mainly
refers to the deformation in the form of changing the wing area and geometric parameters. Its deformation is fairly big, which can ensure that the aircraft can obtain excellent aerodynamic performance at different flight speeds.

The earliest concepts of deformable aircraft date back to the deformable vehicle MAK-10, designed by Russian-born engineer Ivan Makhonine [4].

In 1951, American Bell built the X-5 variable swept-back wing aircraft, which could maintain a swept-back angle of 20°, 40° and 60° at three angles, with the wings changing from minimum to maximum swept-back angles in less than 30 s.

In 2016, Jenett et al. Of MIT designed and developed an active torsional deformation wing structure with discrete distribution and reversible assembly based on ultra light elastomer element[5].

In 2010, Manzo and Garcia of Cornell University proposed a hyperelliptic arc span (HECs) wing structure with spanwise bending based on the angle of albatross wing deformation[6].

In 2011, Lesieutre et al. at Pennsylvania State University designed a flexible truss unit to replace the fixed support structure in a normal wing, allowing for wing span variation.

In 2011, Mestrinho et al. presented a variable-extension wing for small UAVs, made of composite materials and divided into a fixed part attached to the fuselage and a movable part that slides within the fixed part shell.

In 2012, Wang et al. from Nanyang Technological University proposed a single-degree-of-freedom mechanism based on sarrus connecting rods to achieve wing span variation.

In 2012, Woods and Werley of Swansea University, UK, designed a bending wing imitating fishbone structure according to the characteristics of small chord stiffness of fishbone structure[7].

In 2017, Santos et al. of the University of Beira, Portugal, designed wings that can change span length.

In 2018, Yu et al. proposed a design method for a rigid sliding skin. This rigid sliding skin is primarily used on six-degree-of-freedom motion stages.

In 2013, Heo et al. from Korea's Koryo university designed a passive deformable wing with flexible cell core based on deformable honeycomb structure. They respectively studied the deformation of airfoil with three honeycomb cores (chiral, regular and concave hexagon) under static load[8]. The results show that the concave hexagon honeycomb core shows the highest flexibility, and the stress in the local honeycomb wall is lower than that of other parts under shear load, which means that the concave hexagon honeycomb core has the potential to be used in the deformation wing filling structure.

Cornerstone's research team studied a shape-memory polymer skin that could be used on variable chord length wings, using two air pistons filled with heated or cooled gas to control the stretching or shrinking of the shape-memory polymer.

Linkoping University of Sweden encouraged its students to carry out the research of the deformed aircraft, and put forward 12 plans. Through the review, three plans were determined for design, manufacture and demonstration flight, which are respectively: the expansion wing plan, the variable swept wing plan and the combination plan of the two wings. The final result is that the effect of expansion wing is good, the combination plan of the two wings is not obvious, and the test flight of the variable swept wing has not been carried out successfully.

Rediniotis et al. at Texas A&M University have designed a bionic hydrofoil that can be actively deformed by rotating six segments of a spine driven by a shape memory alloy, with metal skins mounted on the outside of the spine, which can interlock without interference during the deformation process.

The existing technologies of research results include: variable swept wing technology, tilt wing technology, X-Wing aircraft technology, etc.

4.2. Domestic research progress.

From the domestic data, the main research contents of the deformable wing focus on the internal deformable skeleton and the external deformable skin. In recent years, Harbin Institute of Technology,
Northwestern Polytechnical University, Nanjing University of Aeronautics and Astronautics and other units have carried out relevant research on the internal deformable structure and external deformable skin of the deformable wing. Bai Peng, Chen Qian, Guo Jianguo, Xu Guowu et al. [9-11] analyzed the aerodynamic and structural characteristics of the telescoping deformation aircraft and the variable swept back and variable swept forward aircraft. Zhang Jie et al. [12] established the dynamic model of variable sweep and variable spread length combined deformation aircraft, and carried out the dynamic response analysis.

In 2016, Zhang Chengchun and others of Jilin University designed a bionic deformed wing of amphibious aircraft based on the characteristics of the wing posture during the diving process of Kingfisher. The wing folded and deformed through the contraction and extension of the expansion bar and its relative motion with the slide. By analyzing the structural form of deformable corrugated sandwich plate and the deformation principle of animal vertebrae, Lv Zhengyang [13] of Harbin Institute of Technology proposed the design idea of deformable wing structure: to realize the large deformation of the whole wing by accumulating small deformation in the deformable truss unit. Lili Gu et al. [14] of Nanjing University of Aeronautics and Astronautics took the pigeon as an object of study, abstracted a bionic structural model based on its flight attitude and skeletal characteristics, proposed a bionic deformation wing scheme with a two-stage layout, and simulated and analyzed pigeon’s different flight states such as cruising and climbing. In addition, Chunlin Gong et al. of Northwestern Polytechnical University proposed a solution based on the Karhunen-Loève method and the Kriging method [15] for the optimization problem of distributed deformable vehicles, and verified the feasibility of the proposed methods.

5. Concluding Remarks
In this paper, the development process of deformable wing technology from its generation to now is summarized. At the same time, the technology of deformable wing is analyzed. It is understood that the existing technology is not enough to give full play to the advantages of deformed wing. At present, the application of deformable wing technology in large aircraft has been developed, but due to the continuous development of new technology and new materials, the technology still has great potential. If the deformable wing technology is popularized in the small self-adaptive aircraft, it will bring a new revolution in this field. At the same time, the role of UAV in civil and national defense will be greatly improved. In terms of development prospects, the technology of deformed wing can also bring new development to the traditional large-scale human controlled aircraft. From the current development point of view, the research of deformed wing UAV is still in the primary stage, and there are many aspects to be improved and in-depth. For example, in the aspect of mechanism design, the existing mechanism scheme can not fully achieve the ideal state of portability, accuracy and large transmission efficiency, and has great improvement space. Therefore, we should try to start from the aspect of new materials.

Further work:
- The dynamic characteristics of the deformable truss with external force constraints need to be further studied;
- A skin structure based on the deformable wing of tetrahedral truss needs to be designed, which can continuously adapt the deformation of truss;
- The method of multi-point control needs to be studied to realize the continuous deformation of plane truss structure, which provides a theoretical reference for the whole deformation of variant aircraft;
- At present, the research is limited to the topology optimization of the structure, without considering the driving mode, which belongs to the passive deformation mechanism. In the next research, the intelligent materials need to be considered, and the structure need to be given the ability of active deformation by controlling the deformation of the intelligent material;
• At present, isotropic materials are used instead of anisotropic materials. In the follow-up study, composite materials with better performance need to be considered to strengthen the mechanical properties of the structure;

• At present, the research of near-space vehicles is at an early stage. In the follow-up research, there is a need to strengthen the capability of the aircraft to achieve long-duration and long-range cruising in near space;

• Research the mesh reinforced membrane materials to enhance the bending load-bearing properties of inflatable beams and thus promote the development of UAV inflatable wings.

Reference

[1] Sofla A. Y. N., Meguid S. A., Tan K. T. and et al Shape morphing of aircraft wing: Status and challenges[J]. Materials and Design, 2010, 31(13): 1284~1292.

[2] Michael D. Skillen and William A. Crossley Modeling and optimization for morphing wing concept generation[R]. NASA CR-214860, 2007.

[3] Abhijit Hiraman Supakar Design, analysis and development of a morphable wing structure for unmanned aerial vehicle performance augmentation[D]. Arlington: The University of Texas, 2007.

[4] Ajaj R, Friswell M, Saavedra Flores E, et al. Span morphing: a conceptual design study[C]/53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA, 2012: 1510.

[5] Jenett B, Calisch S, Cellucci D and et al Digital Morphing Wing: Active Wing Shaping Concept Using Composite Lattice-Based Cellular Structures[J]. Soft robotics, 2017(01): 33-48.

[6] Manzo J and Garcia E Demonstration of an in situ morphing hyperelliptical cambered span wing mechanism[J]. Smart Materials and Structures, 2010, 19(2): 025012.

[7] Woods B K S, Wereley N M and Friswell M Preliminary investigation of a fishbone active camber concept[C]. ASME conference on smart materials, adaptive structures and intelligent systems, Stone Mountain, Georgia, USA, 2012.

[8] Heo H, Ju J, Kim D M. Compliant cellular structures: application to a passive morphing airfoil[J]. Composite Structures, 2013, 106: 560-569.

[9] CHEN Qian, BAI Peng and LI Feng Morphing aircraft wing variablesweep: two practical methods and their aerodynamic characteristics[J]. Acta Aerodynamic Sinica,2012,30(5): 658 ~663.(in Chinese)

[10] GUO Jianguo, CHEN Huijuan, ZHOU Jun and et al Dynamics modeling and characteristic analysis for vehicle with asymmetric span morphing wing[J]. Journal of Systems Engineering and Electronics,2016,38(8): 1951 — 1957. (in Chinese)

[11] XU Guowu, BAI Peng and CHEN Bingyan Analysis on the liftdrag characteristics of new concept morphing aircraft[J].Chinese Quarterly of Mechanics,2013,34(3): 444 — 450. (in Chinese)

[12] ZHANG Jie and WU Sentang Dynamic modeling for a morphing aircraft and dynamic characteristics analysis[P].Journal of Beijing University of Aeronautics and Astronautics,2015, 41(1): 58 — 64 (in Chinese)

[13] Lv Zhengchang Structural Design And Deformation Characteristics Analysis Of Morphing Wing Truss Structure[D]. Harbin Institute of Technology, 2019.

[14] Gu Lili Basic Research on Structure and Driving of Morphing Wing[D]. Nan Jing: Nanjing University of Aeronautics and Astronautics, 2013.

[15] GONG Chunlin, CHI Fenghua, GU Liangxian and et al Optimal control method for distributed morphing aircraft based on Karhunen-Loève expansion[J]. Acta Aeronautica et Astronautica Sinica, 2018, 39(2):121518. (in Chinese)