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A Disruptive Method of Large Volume Elastic Structures Design

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ABSTRACT
This paper proposes that the flexible morphing structure can be main parts of aircraft in the future, which can lose the metal parts weight, achieve large volume deformation and keep on performance guarantee. It also characterized the concept and morphing principle of triangular pyramid morphing structure and hollow constant-strength morphing structure, which is an important part of the flexible morphing structure. It is shown the feature of three-dimensional elastic parts. By comparison of the the flexible morphing structure and the present technology and materials of morphing aircraft, it is described the design of the new aircraft with the flexible morphing structure and the influence for the battle model for in the future.

KEYWORDS
large volume elastic structure; morphing aircraft; large volume deformation; triangular pyramid morphing structure; hollow constant-strength morphing structure

With the development of the aviation industry, the missions of aircraft are becoming increasingly complex. To adapt to varying flight environments and improve flight performance, modern aircraft have begun to adopt intelligent flow control and flight technology control during flight[1], restructuring the aerodynamic layout of the aircraft to achieve optimal flight performance in different flight states[2]. Currently, the reconstruction of aircraft aerodynamic layouts is mainly achieved through the deformation capability of elastic or smart materials themselves[3]. Various types of smart wings with miniature actuators have been successfully developed, as well as “adaptive flexible trailing edge technology”[4] that adjusts wing surfaces according to flight conditions. These technologies mainly achieve minor shape deformations of aircraft wings and cannot yet achieve large-scale elastic deformations of aircraft components, due to the need for high strength in the main structural components of aircraft, as significant deformations of these materials would lead to substantial changes in component strength and make it difficult to ensure their original performance[5]. Some aviation systems have specially set up high awards for technicians who can achieve an aircraft wing area deformation ratio of more than 3[6]. The DARPA has also set the goal of realizing the change of wing area of aircraft by more than 50%[7]. Therefore, if large-scale elastic deformations of aircraft components can be achieved while ensuring their original performance, it would be a revolution for future aircraft. However, this cannot be achieved solely through material deformation and traditional mechanical telescopic deformation; other methods are needed to achieve large-scale elastic deformation of aircraft components.

This article elaborates on a design concept for aircraft component structures, although it has not yet entered the application stage, its unique approach of using structural design instead of material design is innovative in the design concept of future morphing aircraft. If it can enter the practical application stage, the design of morphing aircraft will take a new step forward.

1 Large-Scale Elastic Structure

The intermolecular bonding forces between them act when materials undergo elastic deformation: elongation, contraction, or rotation[8]. Rubber and polymer materials can produce significant elastic deformation, but have lower strength, hardness, and poor high-temperature and high-pressure resistance[9]. Metals can also undergo elastic deformation under external forces, but to a lesser extent, and the strength of the parts after deformation will change[10]. Therefore, if there is a “material” that can achieve large-scale elastic deformation while possessing high strength, hardness, and resistance to high temperatures and pressures, it can realize the large volume deformation of aircraft components while ensuring the performance of the components themselves. This “material” can be replaced by a structural system with metal-like characteristics and certain bearing capacity, which is the large volume elastic structure, mainly composed of tetrahedral deformation structures and hollow constant-strength morphing structure.

1.1 Triangular pyramid morphing structure

The triangular pyramid morphing structure is composed of four regular triangular pyramid, with one side of each of the three triangular pyramid being attached to one side of the central triangular pyramid. When the central triangular pyramid moves left and right (as shown in Figure 1), the three surrounding triangular pyramid always adhere to the sides of the central triangular pyramid and converge with the movement of the central triangular pyramid. The total length of the overall structure, a, will also elongate or shrink with the movement of the central triangular pyramid. This deformable body composed of tetrahedra can change the overall structure length under the action of external forces, and is called a triangular pyramid morphing structure. The degree of deformation is determined by the length of the central triangular pyramid.

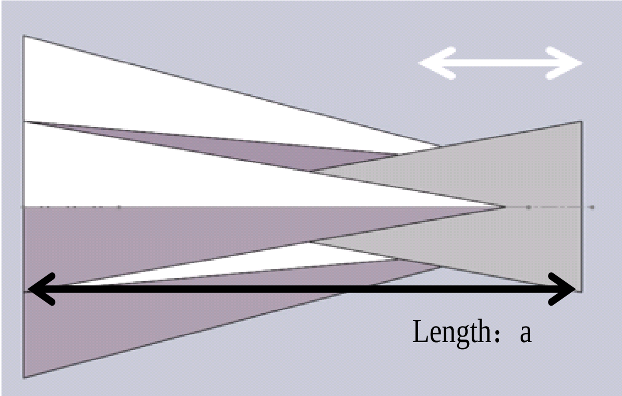

Figure 1 Triangular pyramid morphing structure

Due to the scalability and certain rigidity of the triangular pyramid morphing structure, it can be used to form the surface of elastic parts. The surface of a quasi-spherical or polyhedral structure composed of multiple small-scale (centimeter-level) triangular pyramid morphing structure can expand and contract with the change in the overall volume of the part under external or internal forces, ensuring its integrity is not compromised. Therefore, it is an ideal structure for the outer surface of large volume elastic structural parts.

1.2 Hollow constant-strength morphing structure

In construction, metal pipes often instead of solid metal rods for building because the stress distribution of a cylinder under bending stress is trapezoidal along the radius direction from the axis to the circumference. The stress is maximum at the surface of the cylinder and decreases closer to the axis, so the bending strength of hollow steel pipes is almost the same as that of solid steel rods. This is also done to reduce material consumption and the self-weight of load-bearing components, hence the use of hollow core materials. Similarly, a cylindrical solid steel rod is replaced by the structure shown in Figure 2. The outer cylinder is composed of material with appropriate strength, with four small solid bodies evenly distributed on it, connected to the central small solid bodies with connecting keys. If the material of the connecting keys is appropriate, the entire structure can achieve the same or nearly the same tensile strength as a solid steel rod. This hollow structure is called a constant strength hollow body made of solid materials.

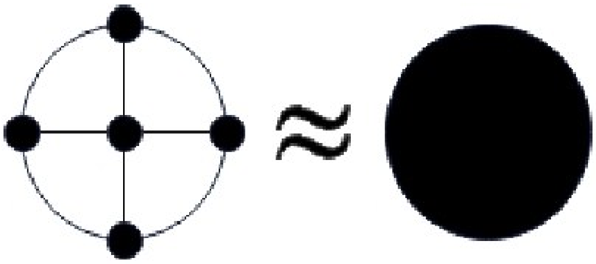

Figure 2 Hollow structure of constant-strength

If the outer shell of the constant strength hollow body in Figure 2 is composed of multiple small-scale (centimeter-level) triangular pyramid morphing structures described in the previous section, and the overall structure of the connecting keys can expand and contract under external forces, then the entire constant strength hollow body can undergo elastic deformation under external forces. Since the degree of deformation of the constant strength hollow body depends on the deformation of the connecting keys, its overall three-dimensional volume change can be very large (as shown in Figure 3). This type of elastic deformation driven by the variation of connecting keys throughout the structure is called a hollow constant-strength morphing structure.

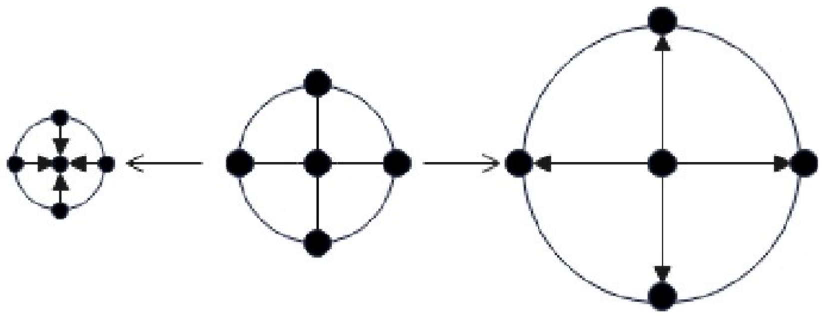

Figure 3 Hollow constant-strength morphing structure

The structure of the connecting keys in the constant strength hollow body is crucial. It must have the strength to support the entire hollow constant-strength morphing structure as a skeleton while possessing the characteristic of variable length to meet the deformation requirements of the overall structure, as shown in Figure 4.

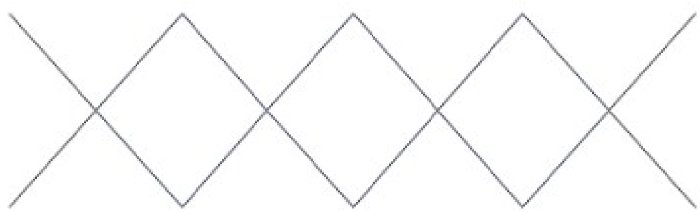

Figure 4 Connecting bond structure

The deformation of this woven structure is achieved by different shape memory materials at intersection points. The red represents one type of shape memory material, while the green represents another one. These materials undergo contraction or expansion under different field effects, as shown in Figure 5.

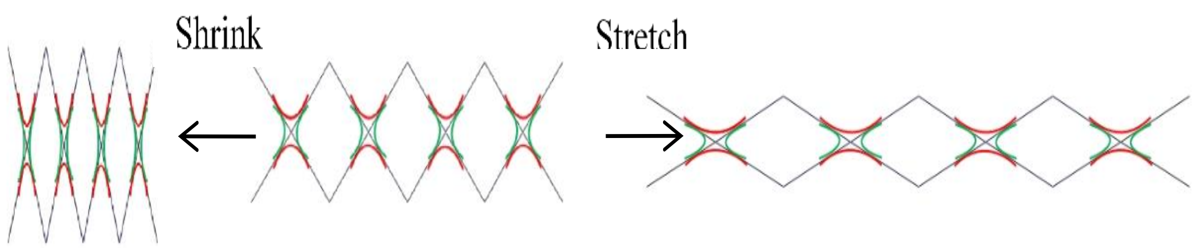

Figure 5 Connecting bond morphing structure

The deformation of shape memory materials can be achieved by field effects, driving the entire connecting key to elongate or shorten, thereby realizing the deformation of the entire hollow constant-strength morphing structure.

1.3 Large Volume Elastic Structural Components

By combining triangular pyramid morphing structure with hollow constant-strength morphing structure, deformable large volume elastic structural components can be formed. The outer surface of the component is composed of multiple small-scale triangular pyramid morphing structures and can be made of high-temperature alloys. This means that the outer surface of the component is made of high-temperature alloys. The interior can be composed of multiple hollow constant-strength morphing structures. The connecting keys use a braided structure and can be made of high-strength steel or aluminum alloys used in aviation, with different types of shape memory alloys at the intersection points of the braided structure to ensure contraction and expansion deformation under different field effects. Apart from spherical structures, various other structures can also be used, for example, constant strength hollow structures resembling diamonds in Figure 6), if changes occur in the connecting keys, the overall structure can undergo volume deformation. This not only meets the deformation requirements but also possesses the outer characteristics of metal structures such as high temperature resistance and abrasion resistance.

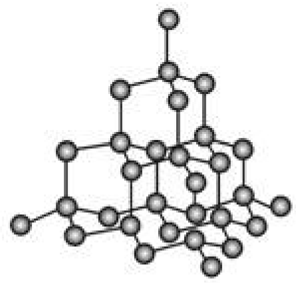

Figure 6 Hollow diamond-like constant strength morphing structure

The main feature of large volume elastic structural components is that the entire component can undergo significant volume changes under external force control (such as field effects), achieving the outer characteristics of high hardness and high temperature resistance typical of metal structures. The biggest difference from existing aircraft deformation components is that existing deformation components can only undergo motion deformation, such as bending and flipping, and cannot change the volume of the component. In contrast, large volume elastic structural components can undergo significant volume changes.

If large volume elastic structural components are used to construct aircraft fuselages, each component is of small scale and distributed across the surface of the fuselage. This allows for excellent stealth performance of the aircraft while ensuring its flight performance. During normal cruising, a portion of the large volume elastic structural components on the aircraft surface can undergo deformation through field effects, forming a locally faceted structure on the aircraft surface to reduce radar wave reflection. When high-speed flight is required, the group of large volume elastic structural components forming the facets deforms, retracting into the aircraft fuselage and forming a smooth surface.

2 Large Volume Elastic Structure for Aviation Field

2.1 Limitations of Existing Aircraft Deformation Techniques and Materials

The generalized aircraft deformation techniques include fuselage deformation, tail deformation, landing gear retraction, powerplant deformation, and wing deformation[11]. Current so-called intelligent deformable aircraft typically only involve wing deformation, purposefully altering wing characteristics such as sweep, span, and curvature to effectively increase wing efficiency[12]. Among these, changing span and wing area has the most significant effect. For example, during cruising, an aircraft requires high aspect ratio wings with large wing areas, while high flight speeds necessitate low aspect ratio wings with smaller wing areas[13]. Combat situations require aircraft with stealthy wing structures to greatly reduce the aircraft's radar cross-section (RCS)[14]. The purpose of deformable wings is to integrate all these characteristics to fundamentally improve aircraft performance[15].

The technology of aircraft deformation has evolved from its early origins in simple mechanical devices to its current state utilizing smart materials and advanced control techniques, such as deformations along the chordwise axis, spanwise axis, simultaneous chordwise-spanwise deformation, or rotation of the wing surface axis, enabling continuous modification of the wing's shape, ultimately leading to exceptional flight performance. Techniques such as wing folding, wingtip deflection, wing extension, rotor tilt, adaptive wings, active aerodynamic elastic wings, sliding skins, flapping wings, rotor/wing hybrids, etc[16]. These technologies cannot be achieved with traditional materials, hence, the mainstream research direction for deformable wings currently involves using one or more smart materials[17]. The main smart materials include shape memory alloys, cross-linked polyolefins, shape memory polyurethanes, and liquid crystal elastomers. However, these materials have significant drawbacks as deformation wing materials. For example, shape memory alloys have slow response speeds and difficult dynamic control; cross-linked polyolefins have low deformation temperatures and low material strength; although the soft segments of shape memory polyurethanes have reversibility, they have low glass transition temperatures; while liquid crystal elastomers have bi-directional reversible deformation, they are difficult to process, and spontaneous reversible deformation of monodomains in liquid crystal elastomers has not been reasonably explained[18]. The most important thing is that these materials cannot achieve large-scale deformation of the wing.

The DARPA has set some benchmarks for the deformation capability of deformable aircraft: a 20° change in wing sweep angle, a 200% change in aspect ratio, and a more than 50% change in wing area. These requirements have been proposed for future deformable aircraft under the premise of using smart materials for traditional designs[19]. Whether it is possible to overcome the limitations of materials themselves on the degree of deformation, while ensuring the strength of the wings themselves, and increasing the degree of deformation of deformable wings, requires vigorous research and development on large volume elastic structures.

2.2 Impact of Large Volume Elastic Structures on Future Aircraft Design

Large volume elastic structures, composed of appropriate materials to form triangular pyramid morphing structure and hollow constant-strength morphing structure, can achieve deformation levels exceeding 300%. This not only elevates existing deformation techniques but also pioneers a new aircraft design concept.

The current deformable aircraft typically involve motion deformation of components during flight, such as changes in wingtip position, angle adjustments of trailing edge control surfaces, flaps, and slats[20]. This deformation technique can only achieve different flight effects by altering the actions of some components within the established overall structure of the aircraft. Currently, there is no design that changes the shape of the entire aircraft during flight. For example, at the beginning of a flight, the aircraft fuselage is designed with multiple facets for excellent stealth. When preparing to attack a target detected from a long distance, the facets on the fuselage quickly retract, presenting a smooth curved surface, while the wings also retract, reducing wing surface area, transforming the appearance of the aircraft into that of a cruise missile for a high-speed approach to the target. When preparing to depart after an attack at a designated location but detected by enemy aircraft preparing for aerial combat, the wings rapidly extend, providing the aircraft with high maneuverability for combat. Due to the ability of large volume elastic structural components to surpass material deformation limitations and achieve significant volume deformation of components through structural changes, it becomes feasible to achieve both wing retraction/expansion and changes in fuselage shape. These scenarios, reminiscent of scenes seen only in science fiction movies, hold promise for realization in the future with the support of large volume elastic structures. Currently, the main issues encountered in the practical application of large volume elastic structures include.

Selection of connecting key materials: The connecting keys, as supports for hollow constant-strength morphing structure, determine the strength, toughness, and application range of the structure. Therefore, material selection needs to be very cautious, not only to assess whether it can support the strength of individual structures but also to consider the degree of deformation of shape memory alloys at the connections.

Difficulty in small-scale processing of large volume elastic structural components: The hollow constant-strength morphing structure and triangular pyramid morphing structure within large volume elastic structures are small-scale (centimeter-level) components, making the processing technology of these components crucial. Factors such as the welding of shape memory alloys and the roughness of triangular pyramid processing can affect the overall deformation of components.

Complexity of deformation control for large volume elastic structures: Deformation systems generally include control systems, power systems, and stop systems. The control system and power system of large volume elastic structures are similar to those of smart skins, both utilizing field effects for control. However, the stop system is very complex, and current designs use internal filling for stopping.

Introducing the design concept of large volume elastic structures, future aircraft design will no longer need to balance high-speed and low-speed flight capabilities, endurance performance, maneuverability, and stealth performance through aerodynamic layouts. These requirements can all be met through overall deformation during flight to adapt to the demands of different missions while achieving stealth, high maneuverability, and high cruising speeds.

3 Conclusion

At present, various countries have their own design concepts for future sixth-generation fighters, which can generally be divided into three versions: high-altitude and high-speed fighter, UAV fighter, and what is referred to as an enhanced fifth-generation fighter. Therefore, if the new generation of aircraft is based on large volume elastic structures as the main components, this new perspective in aircraft design could contribute to the development of aviation industry in the whole world.

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