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Research on the Application and Development Prospect of Flexible Skin Technology in the Aerospace Field

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Abstract. As a cutting-edge innovation in the aerospace field, flexible skin technology is profoundly transforming the design and manufacturing of aircraft for various purposes. This paper systematically elaborates on the breakthrough progress of flexible skin technology in basic structure, intelligent perception, thermal protection, and space applications, and analyzes its key technical paths in material innovation, manufacturing processes, and system integration. Research shows that the application of flexible skin technology enables real-time adjustment of the aerodynamic surface of aircraft, significantly improving aerodynamic performance, stealth capability, and full-condition aerodynamic efficiency. With the advancement of materials science, manufacturing processes, and the interdisciplinary integration of artificial intelligence, flexible skin technology is moving towards intelligence and multi-functionality, which will bring disruptive changes to the next generation of aircraft.

Keywords: adaptive aerodynamic optimization, lightweight and integration, intelligent perception and monitoring, thermal management and protection

1. Introduction

Flexible skin technology is one of the important technologies to achieve a revolutionary improvement in aircraft performance, attracting great attention from countries around the world that have invested substantial resources in related research. As a typical bionic design, flexible skin technology enables continuous, smooth, and flexible deformation of aircraft surfaces and specific components, similar to fish and birds. This design subverts the traditional segmented and rigid deformation mode, providing technical support for significantly improving aircraft aerodynamic performance, stealth capability, and adaptability under different flight conditions.

From the perspective of technical evolution, flexible skin technology has gone through three stages: concept exploration, material breakthrough, and system integration. In the late 20th century, researchers mainly focused on the theoretical feasibility of flexible skin; in the early 21st century, with the breakthroughs in materials science and intelligent manufacturing technology, flexible skin entered the experimental verification stage. In recent years, with the maturity of additive manufacturing (e.g., 3D printing technology) and flexible electronics (e.g., flexible printed circuit boards), flexible skin is rapidly moving from the laboratory to engineering applications.

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This paper reviews the application of flexible skin technology in aerospace, highlighting technical advancements and exploring future prospects and challenges. It emphasizes the technology's role in transforming aircraft shape and functions, enhancing aerodynamic efficiency and environmental adaptability. The research signifies a shift from traditional aircraft design to intelligent, integrated structures, establishing a foundational material and structural basis for the next generation of aircraft and spacecraft.

2. Main application fields of flexible skin technology

2.1. Adaptive regulation of aircraft aerodynamic shape

The most prominent application of flexible skin technology in the aerospace field is the realization of real-time adaptive regulation of aircraft aerodynamic shape. Due to mechanical structure limitations, traditional aircraft have numerous gaps between control surfaces, which not only generate additional aerodynamic drag but also cause severe radar wave scattering, thereby limiting their stealth performance. In contrast, flexible skin technology forms a continuously deformable skin that can deflect with the control surfaces by embedding elastic conductive materials in a high-strength fiber matrix, "seamlessly" covering the junctions of control surfaces and physically eliminating radar wave scattering caused by mechanical gaps.

On China's latest generation of stealth fighter jet J-20, flexible skin is widely used in movable parts such as the leading and trailing edge flaps of wings, ventral fins, and DSI inlet adjustable panels. Public images show that there are almost no obvious gaps at the wing-fuselage junction and the root of the all-moving vertical tail of the J-20, demonstrating extremely high process consistency. This design not only reduces radar wave reflection but also significantly improves the aircraft's aerodynamic efficiency. In contrast, traditional fighter jets such as the J-10 still adopt the traditional "metal cover + serrated edge" mechanical stealth design, which cannot completely eliminate gaps. Moreover, wear and gap changes are prone to occur during repeated operations, leading to a decline in actual stealth performance over time.

In the civil aviation field, flexible skin technology provides key support for the development of adaptive wings. By integrating driving elements such as shape memory alloys and piezoelectric materials, flexible skin can automatically adjust the airfoil camber according to flight conditions (e.g., takeoff, cruise, landing) to achieve optimal aerodynamic efficiency. Relevant research indicates that such adaptive airfoils can improve aircraft aerodynamic efficiency by 10%-15% and fuel efficiency by 5%-8% without increasing structural weight, meaning civil aviation aircraft will operate more economically and efficiently [1].

2.2. Intelligent perception and real-time monitoring

Another important application direction of flexible skin technology is to construct a distributed intelligent perception network on the aerodynamic surfaces requiring monitoring, realizing the monitoring of air flow status, pressure distribution, and structural stress status on aircraft surfaces. Researchers from Huazhong University of Science and Technology developed a high-resolution rapid reconstruction method for flow fields based on flexible intelligent skin, which successfully achieved real-time perception and reconstruction of the flow field around airfoils through a flexible sensor array distributed on the wing surface. During aircraft flight, flexible intelligent skin provides in-flight data acquisition capabilities that traditional wind tunnel test methods such as temperature-sensitive paint (TSP) and pressure-sensitive paint (PSP) do not possess, thereby achieving real-time

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monitoring effects that cannot be achieved by traditional means. The researchers developed a dual-branch channel attention fusion model based on an encoder-decoder network architecture, realizing rapid prediction of 2D airfoil flow fields with a relative error of only 3.68% and reconstruction of global flow field distribution with higher spatial resolution, with the relative error controlled within 5% [2]. This breakthrough makes it possible to real-time identify boundary layer transition, separated vortex shedding, and stall positions, providing important guarantees for flight safety.

2.3. Thermal protection and thermal management

Facing extreme thermal environments in hypersonic aircraft and reentry spacecraft, flexible skin technology offers a promising thermal protection solution. Inspired by the working principle of human skin sweat glands, researchers have developed an adaptive two-layer thermal protective skin, which realizes water transportation based on the structure of inner hollow porous TPU/PVC fibers embedded in silicone, and the outer PET spacer fabric is responsible for water storage and transpiration [3]. This bionic thermal protection system has good biaxial deformability (approximately 150%) and can reach a comfortable temperature (approximately 46°C) within 1 second under a high heat flux (420 kW/m²). Finite element simulation shows that the spacer fabric with an optimized thickness of 9 mm can reduce the surface temperature of 1000°C to 20°C in 0.7 seconds [3]. This innovative design provides an effective solution for dealing with intense chemical flames or aerodynamic heating, and is suitable for protecting the extreme thermal environment of spacecraft during reentry into the atmosphere and for the leading edge thermal protection of hypersonic aircraft. In addition, flexible thermal management systems based on phase change materials, microchannel cooling, and thermoelectric conversion have also been applied in the aerospace field. These systems can independently adjust surface thermal characteristics according to ambient temperature to achieve active thermal management, providing reliable protection for key components like electronic equipment and propulsion systems in high-temperature environments.

2.4. Space environment adaptive applications

Flexible skin technology has potential applications in space exploration, as demonstrated by the SHIELD team's elastic intelligent "skin" at Lamar University, designed to protect space robots' joints and circuits. This intelligent skin adopts a silicone formula and attempts to add bismuth nanoparticles to enhance radiation resistance. In space, if robots are directly exposed, their joints and sensitive components will be threatened by cosmic radiation, extreme temperatures, and space debris. The intelligent skin samples of the SHIELD team will be exposed outside the International Space Station for six months. After returning to Earth, the research team will test their tensile strength and radiation exposure level and compare them with the control samples left on the ground. This research is crucial for the durability of robotic systems in future long-term space missions [4].

In the field of satellite technology, the concept of flexible skin is further extended to the development of flexible solar wings. China's Yinhe Space Lingxi-03 satellite, as the first satellite using flexible solar wings, has successfully achieved an innovation in the satellite energy system. These wings consist of thin flexible solar panels, only about 1 mm thick, and when deployed, they extend to 9 meters long and over 2.5 meters wide, while folded they measure around 5 cm in thickness. This innovative design significantly reduces the occupation of satellite volume and weight, meets the high-power energy demand of satellites, is suitable for multi-satellite stacked launch mode, and helps the entire industry reduce costs and increase efficiency [5].

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3. Key technologies and innovative breakthroughs of flexible skin

3.1. Material innovation and structural design

The core breakthrough of flexible skin technology comes from new materials and microstructure design. In recent years, various intelligent materials with special properties have been introduced into flexible skin systems, including shape memory alloys (SMA), ionic polymer-metal composites (IPMC), and piezoelectric materials. These materials adapt their shape or properties in response to electric field, temperature, or magnetic field changes, enhancing the skin's adaptive capabilities.

Metamaterial concepts in structural design allow new skin materials to achieve performance beyond traditional materials. Researchers developed materials with zero Poisson's ratio, negative stiffness, or programmable stiffness by designing special microstructures. Such materials can be easily deformed in the in-plane direction to reduce the requirements on the drive system, while maintaining sufficient stiffness in the out-of-plane direction to maintain the aerodynamic shape.

The advancement of additive manufacturing technology provides the possibility for the realization of complex microstructures. Through high-precision 3D printing, researchers can manufacture flexible skins with multi-level topological structures, which regulate the mechanical properties of materials at the microscale, enabling a single material to meet multiple seemingly contradictory requirements. For example, the "morphing skin" that has attracted much attention in the aerospace field achieves the perfect combination of extremely small in-plane stiffness and large out-of-plane stiffness through micro-architecture design [1].

3.2. Manufacturing processes and digital production

The industrial application of flexible skin technology is inseparable from the innovation of manufacturing processes and the support of digital production systems. China's breakthroughs in aircraft manufacturing equipment have provided strong support for flexible skin technology. In 2025, the successful development of the world's first 1230-ton "dual-mode forming" skin stretching machine achieved 0.1 mm-level precision "one-click forming", supporting multi-point flexible molds and digital twin systems, and promoting the penetration rate of domestic equipment in the aviation field to exceed 80% [6].

Traditional skin stretching machines apply precisely controlled tensile forces at both ends of metal sheets through special equipment to make the material reach a plastic deformation state, and then press it on the pre-designed mold surface to form the required three-dimensional curved shape. In contrast, the new generation of skin stretching machines integrates digital twin, Internet of Things, and artificial intelligence technologies, which can simulate and optimize the entire forming process in a virtual space, greatly improving the first-pass yield. According to reports, the forming success rate has increased from 60% of traditional processes to more than 95%, the construction period has been reduced by more than 70%, and the cost has been reduced by 35% [6].

In terms of production line construction, Hangyu Intelligent Manufacturing Co., Ltd. is building the largest aircraft skin production line in the Asia-Pacific region in Shenbei New District, Shenyang. The first phase of the project has an investment of 300 million yuan and covers an area of 23,000 square meters. After completion, it will have a production capacity of 16 aircraft sets per month and 192 aircraft sets per year. This production line will cover the entire manufacturing process of skins for multiple models including Airbus A220, A320, C919, and C929. The delivered finished parts have a uniform stress distribution, which can significantly improve skin strength [7].

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3.3. Intelligent sensing and system integration

The intelligent development of flexible skin technology relies on the innovation of high-performance sensing systems and efficient integration methods. The latest progress in distributed optical fiber sensors, flexible capacitive strain gauges, and conductive nanomaterials enables the embedding of large-scale sensing networks in the skin without affecting aerodynamic performance.

In terms of system integration, multidisciplinary optimization design methods have become the key to solving complex engineering problems of flexible skin. The flexible skin system involves the intersection of multiple disciplines such as fluid mechanics, structural mechanics, materials science, electronic engineering, and control theory, and traditional serial design methods are difficult to meet the requirements. The collaborative design platform based on machine learning can simultaneously consider multiple objectives such as shape adaptive efficiency, stealth performance, structural weight, and system reliability to generate optimal design schemes.

The dual-branch channel attention fusion model from Huazhong University of Science and Technology is a typical case of integrated design of flexible skin systems based on deep learning. This model is based on an encoder-decoder network architecture, realizing fast and accurate flow field prediction, and providing an efficient tool for the optimal design of flexible skin [2].

4. Technical challenges and future trends

4.1. Current technical bottlenecks and challenges

Despite the significant progress made in flexible skin technology, challenges still exist in practical applications. Material durability is the primary issue. Flexible skin is prone to fatigue damage during repeated deformation, leading to performance degradation or even failure. Especially under extreme environmental conditions such as strong radiation in space and thermal oxidation in high-temperature environments, the long-term stability of materials remains to be verified.

Drive system efficiency is another major challenge. Achieving macro shape changes requires a huge energy input, while the energy conversion efficiency of most current intelligent materials is relatively low, making it difficult to meet the harsh requirements of aerospace. At the same time, the response speed, power density, and reliability of the drive need to be further improved.

System integration complexity is also an issue that cannot be ignored. Integrating sensing, driving, control, and communication functions into a thin and flexible skin while ensuring system reliability and maintainability places extremely high requirements on engineering design. Especially for large aircraft, the weight penalty and energy demand of the flexible skin system may offset the performance advantages it brings.

In addition, testing and verification methods are also challenges faced by flexible skin technology. The certification standards for traditional aerospace structures are not fully applicable to flexible variable structures, and new testing methods and evaluation standards need to be developed, which to a certain extent delays the industrialization process of the technology.

4.2. Future development trends

With the continuous emergence of new materials, new processes, and new technologies, flexible skin technology is moving towards a high degree of intelligence, deep integration, and wide applicability.

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Future flexible skin will pay more attention to multi-physics coupling design, realizing closed-loop control of perception-decision-action-communication through the integrated innovation of materials-structure-functions. Skin-like flexible skin may become a standard configuration for the next generation of aircraft, which can not only adaptively adjust the aerodynamic shape but also independently adjust surface characteristics according to environmental changes, such as controlling boundary layer transition through microstructure deformation or optimizing electromagnetic wave scattering characteristics through surface impedance adjustment.

Intelligent manufacturing technology will greatly improve the production efficiency and quality consistency of flexible skin. Based on the full-life cycle management of digital twins, precise control of the entire process from material preparation, structural forming to function integration is realized. The advancement of additive manufacturing technology will make it possible to directly print electronic circuits and functional components in the skin, further promoting the development of flexible skin towards lightweight, high performance, and low cost.

In the field of space applications, flexible skin technology will provide key support for long-term extraterrestrial missions. The space test of the SHIELD team at Lamar University marks the official entry of flexible protection systems into the space verification stage. In the future, inflatable space capsules, solar sails, and radiation protection systems based on flexible skin may become standard configurations for space exploration [8,9].

5. Conclusion

As a disruptive innovation in the aerospace field, flexible skin technology is leading a profound transformation in aircraft design concepts. This paper systematically analyzes the applications of flexible skin in adaptive regulation of aerodynamic shape, intelligent perception and structural health monitoring, thermal protection and thermal management, and space environment adaptability, and sorts out its key technical breakthroughs in material innovation, manufacturing processes, and system integration.

Research shows that flexible skin technology has gradually moved from the laboratory concept verification stage to engineering applications, and has demonstrated excellent performance in advanced equipment such as China's J-20 fighter jet and Yinhe Space flexible solar wings. With the deep integration of materials science, manufacturing technology, and artificial intelligence, flexible skin is moving towards multi-functional integration, intelligence, and large-scale application.

In the future, the advancement of high-end equipment like 1230-ton dual-mode forming skin stretching machines and projects such as the Shenyang large skin production line will reduce manufacturing costs of flexible skin and broaden its applications from aerospace to civil sectors. This technology will integrate with cutting-edge innovations like artificial intelligence, digital twins, and high-performance computing to evolve into an intelligent skin system that mimics biological skin characteristics. The technology's maturity may redefine aircraft performance and reshape the aerospace industry, offering essential support for air transportation, space exploration, and national defense. For China, capitalizing on flexible skin technology and overcoming key technological barriers is vital for establishing a self-sufficient industrial chain and achieving its aerospace ambitions.

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