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Challenges and Opportunities of Smart Aircraft Stealth Skin: Perspectives from Self-Sensing and Electromagnetic Absorption Compatibility

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1. The need to develop smart aircraft stealth skin

Aircraft skin, as the primary outer cladding of an aircraft, was initially designed to perform a single mechanical load-bearing duty [1]. From the Wright brothers' early wooden cloth structures [2] in the 1900s to sheet metal structures [3] and then to composite materials [4], the evolution of aircraft skins was fundamentally driven by the pursuit of greater strength and lighter weight [5]. However, this single-function enhancement in structural strength cannot further improve aircraft performance in areas such as flight control and fault warning. Therefore, over the past two decades, aircraft skin research has been seeking a substantial breakthrough in transitioning from a traditional structural load-bearing component to an integrated system with self-sensing capabilities, with increasing requirements for multimission, multiscenario, and multienvironment adaptability (Fig. 1(a)). This research trend can enhance the interaction capabilities between aircraft and their external environments, thereby improving performance aspects such as safety, reliability, and aerodynamic efficiency. For example, with the installation of flexible sensitive arrays or thin-film sensors in the skin layer, self-sensing skin can allow the real-time sensing of aerodynamic parameters around an aircraft, such as the flow field distribution, pressure gradient, and angle of attack variation [6,7], thereby increasing flight safety and efficiency. Furthermore, embedding fiber Bragg gratings and piezoelectric films [8–10] can establish signal monitoring networks within the material, enabling the precise detection of crack propagation and fatigue damage in skin structures during long-term service. This can provide critical data for aircraft safety operations and lifespan prediction. While this large number of embedded sensing elements endows the airframe skin with sensing capabilities, it increases manufacturing complexity and maintenance costs while compromising structural integrity [11]. Flexible smart skin that can be laminated on curved surfaces is desirable for self-sensing on an aircraft [12–14]. Integrating multifunctional sensing units into large flexible skins enables the real-time monitoring of multiple physical quantities [7,15,16] and has potential as a novel approach for measuring multiple physical quantities in the future.

Moreover, efficient electromagnetic (EM) absorption can optimize the concealment performance of aircraft skin and guarantee system operation stability and EM compatibility, one of the indispensable core technologies for modern aircraft (Fig. 1(a)). A common approach to imparting EM absorption capabilities to aircraft skins involves coating the existing skin structure with a layer of EM-absorbing materials (EAMs), which can absorb and attenuate incident EM waves, convert their EM energy into thermal energy, and dissipate it. Ferrite-based materials [17,18] were among the earliest EM wave absorbers studied. Their high magnetic loss properties enable the conversion of incident EM waves into thermal energy, thereby achieving effective absorption. Additionally, carbon-based materials [19,20] exhibit outstanding dielectric loss characteristics. Through mechanisms such as conductive loss and polarization relaxation, they diversify the physical pathways for EM absorption, further enhancing the stealth performance of aircraft. They were the earliest EAMs used for EM absorption [21,22]. Subsequent studies have revealed that designing nanocomposite materials with multiple reflection–absorption pathways and optimized impedance matching can effectively enhance the EM absorption performance [23–26]. Over the past decade, EM absorption structures have been combined with topological design based on material property optimization. Multilayer metamaterial structures, constructed by the gradient stacking of functional layers with distinct EM properties, and EM metasurface structures formed by utilizing the resonant characteristics of periodic EM surface arrays, provide effective pathways for broadband EM wave absorption [27–29]. Furthermore, to address the growing demand for multiband stealth and EM absorption, numerous studies have explored the dynamic reconfiguration of absorption bands by sensing the environment and driving the adaptive deformation of materials and structures [30–32]. The effective integration of sensing and adaptive absorption technologies better meets the current need for EM wave absorption across diverse scenarios and frequency bands, warranting greater attention from the research community.

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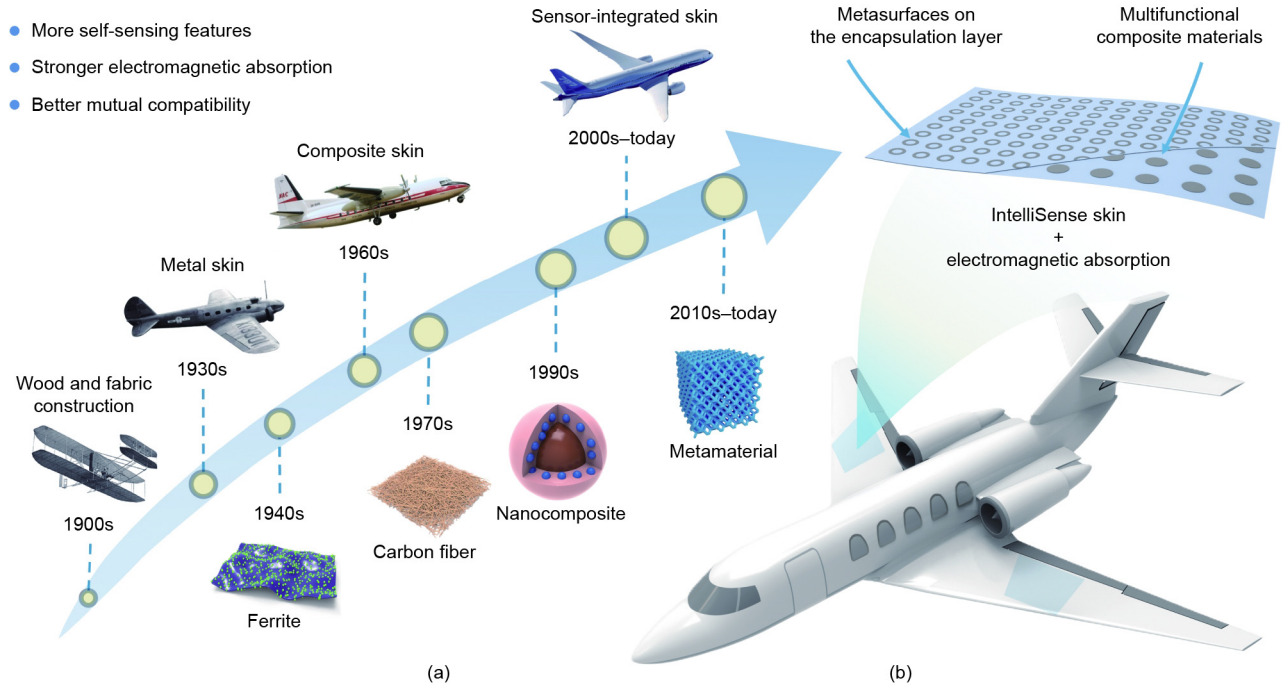

Fig. 1. (a) Brief chronology of the evolution of aircraft skin and electromagnetic absorbing materials, focused mainly on their parallel development. (b) A schematic diagram of smart aircraft stealth skin. In the future, compatibility between self-sensing and electromagnetic absorption functions is expected to be achieved.

Smart aircraft stealth skin is an innovative technology that will significantly enhance overall aircraft performance, for example, by enabling information interaction with the aerodynamic parameters, structural state monitoring, and superior EM shielding. These advances will undoubtedly improve the safety, reliability, and overall capabilities of aircraft, making it possible to satisfy intelligent, multimission requirements. However, recent research on smart aircraft stealth skin has primarily followed the simplistic concept of functional decoupling, embedding sensing devices within the skin structure to achieve sensing capabilities, and applying stealth coatings to the outer layer for EM absorption [33,34]. While this "function separation" approach improves individual metrics in isolation, it overlooks subsystem coupling, which not only increases system weight and manufacturing complexity but also reduces adaptability and multifunctional integration capability. This "function separation" approach contradicts the future aircraft requirements for integration, lightweight construction, and low-cost maintenance, and therefore cannot meet the urgent demands of future aircraft for multimission, multiscenario, and multienvironment adaptability. Future research into "sensing–EM absorption" new multifunctional composite materials, new functionally retentive structures, and new integrated fabrication processes can systematically resolve the spatial and function conflicts between self-sensing and EM absorption and then achieve deep compatibility between the two, enabling the aircraft skin to possess self-sensing capabilities and EM absorption functions simultaneously. Therefore, we believe that shifting the smart aircraft stealth skin design from "discrete function integration" to "ontology function fusion" to fundamentally break functional isolation is the inevitable path for the future development of aircraft skin (Fig. 1(b)).

2. Promoting smart aircraft stealth skin development: Challenges and opportunities

Smart aircraft stealth skin should serve as the "smart outer layer" of the aircraft, capable of both sensing operational conditions (such as airflow, pressure, and temperature) and mitigating EM threats through absorption and shielding to enhance overall performance. The development of such aircraft skin has become an important direction for the evolution of future aircraft toward a high degree of intelligence and integration. The core objective has transcended the enhancement of singular functional parameters, instead focusing on the construction of a multifunctional synergistic "functional composite" that achieves systematic, integrated, and deep integration between structural bearing, environmental sensing, EM absorption, and other multidimensional forms of performance. Nevertheless, constructing such multifunctional and deeply coupled structural systems still presents significant technical challenges.

2.1. Challenges in the development of smart aircraft stealth skin

Despite the attractive conceptual prospects, the technical route to achieve the deep integration of self-sensing and EM absorption is still an uphill climb. The main challenges relate to the following three major dimensions:

(1) The inherent contradiction of material functional properties. As shown in Fig. 2(a), self-sensing and EM absorption impose fundamentally contradictory requirements on material properties. Typically, self-sensing materials demand a sensitive and stable electrical response to changes in external physical quantities [35]. This necessitates that the conductive network within the self-sensing material undergo significant changes during minute deformations, causing abrupt alterations in electrical properties such as electrical resistance. Conversely, EAMs often rely on robust EM dissipation mechanisms. This requires absorbers to possess stable and continuous conductive or dielectric loss networks to ensure the dissipation of EM wave energy. Increasing material conductivity benefits EM absorption, yet an excessively continuous conductive network may decrease the sensing accuracy or cause signal distortion [36–38]. Moreover, differences in functional properties necessitate the ability of sensing-absorbing materials to maintain high-performance absorption capabilities even under deformation. However, current research on material absorptive properties often focuses on optimizing thickness matching, with

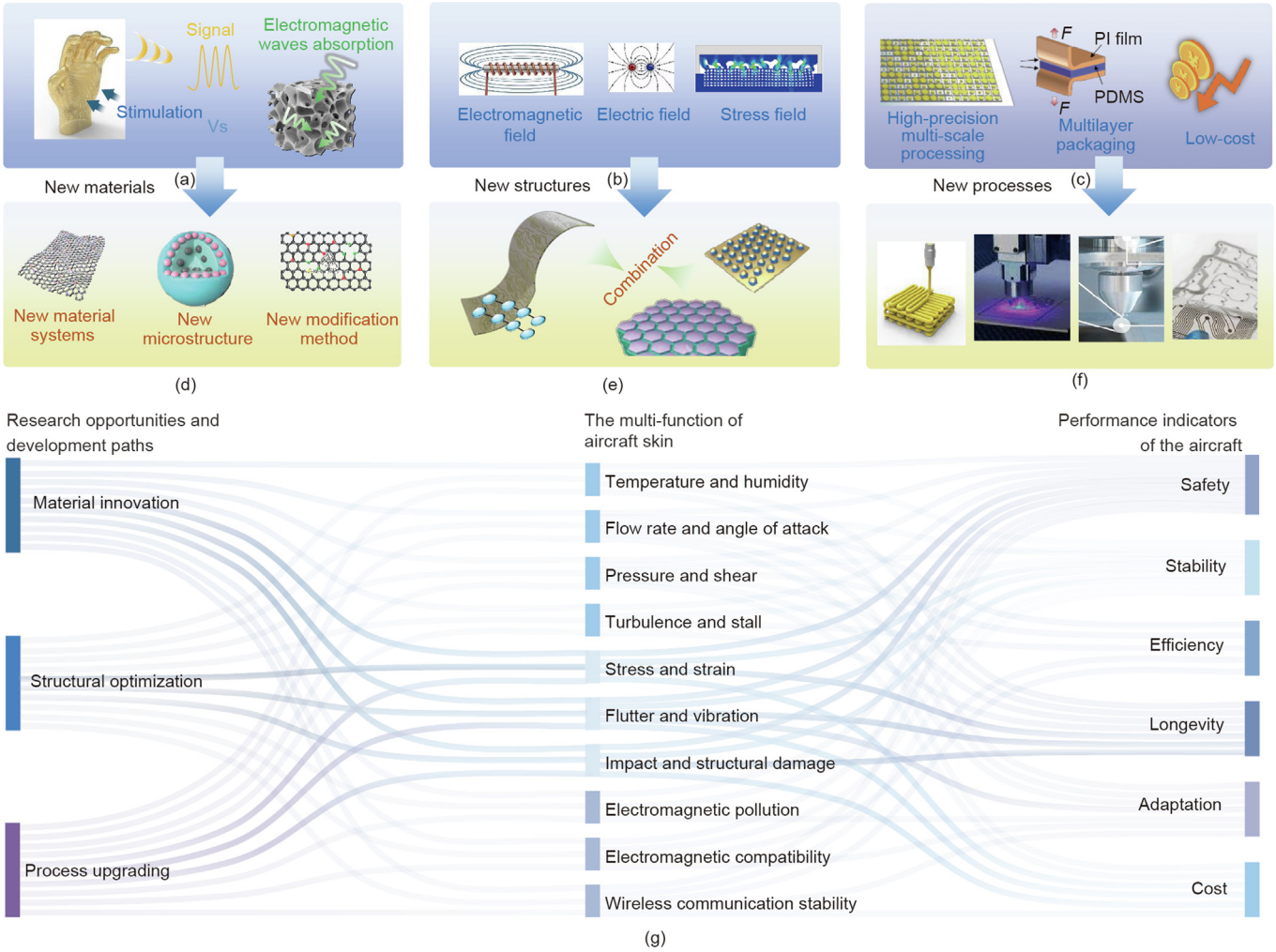

Fig. 2. The challenges and prospects of future aircraft skin. (a) The inherent contradiction of material functional properties. (b) Theoretical and technical bottlenecks in structural optimization design. (c) Immaturity of manufacturing technology and system integration. PI, PDMS, and *F* stands for polyimide, polydimethylsiloxane, and peel force respectively. (d) Development and system optimization of multifunctional composite materials. (e) Collaborative optimization of the sensing–electromagnetic absorbing array architecture. (f) Highly integrated manufacturing and systematic flexible construction. (g) Link between development paths, skin functionality, and aircraft performance. The lines show the path from research and development to the realization of multifunctional integration to the enhancement of aircraft performance.

limited attention given to how material deformation affects absorptive performance. Consequently, designing multifunctional composite materials that simultaneously achieve high-performance sensing and outstanding EM absorption remains among the most challenging research objectives.

(2) Theoretical and technical bottlenecks in structural optimization design. Self-sensing materials typically require surface microstructures (such as pyramids, sandpaper, or columnar structures) to increase deformation under loading, thereby increasing the sensing sensitivity and range [39,40]. However, such surface microstructures often possess geometric scales that are mismatched with the operating wavelength [41,42], which may degrade the impedance-matching performance of the material and thereby weaken its EM absorption capability. Furthermore, sensing in smart stealth skin typically relies on electrical signal changes induced by structural deformations [12,43]. However, these structural deformations often lead to variations in stealth performance. Owing to the current lack of reliable cross-physical coupling modeling and simulation tools, it is difficult to effectively predict and optimize the synergistic effects between materials and structures under complex operating conditions. Thus, achieving both excellent sensing performance and efficient EM wave absorption through structural optimization remains challenging (Fig. 2(b)).

(3) Immaturity of manufacturing technology and system integration. The manufacturing of smart aircraft stealth skin involves the integration of multiple heterogeneous components, which imposes stringent requirements for fabrication precision and consistency. However, current manufacturing technologies still struggle to achieve the three critical indicators of large-area coverage, fine-scale integration, and low-cost mass production simultaneously. In addition, the skin must be suitable for practical aviation applications, capable of conforming to large curved surfaces, minimizing the increase in structural weight, and ensuring long-term stability under harsh environmental conditions. From research to practical implementation, the lack of a high degree of compatibility in the overall process chain has hindered the engineering and strategic deployment of this technology to a certain extent (Fig. 2(c)).

2.2. Key opportunities for promoting smart aircraft stealth skin development

Despite these challenges, the future development path of smart aircraft stealth skin is full of opportunities. In particular, considering breakthroughs in material science, structural design, and manufacturing process systems, a universal platform for self-sensing and EM absorption integration may gradually become a reality.

(1) Development and system optimization of multifunctional composite materials. As shown in Fig. 2(d), material technology serves as the core enabler for integrated sensing-absorption functionality. Emerging multifunctional materials, such as graphene and MXenes [19,23,44,45], combine a high specific surface area with excellent conductivity, enabling their use not only as strain sensors but also for efficient EM absorption through multiscale conductive networks. By further constructing heterogeneous interfaces within graphene and MXene composites, the abundant interfacial structures enhance EM absorption through polarization losses, while the controllable conductive networks maintain piezoresistive sensitivity during deformation [46,47]. Furthermore, on the basis of material selection, the design of microstructural engineering, such as constructing "porous structures" and controlling the configuration of conductive and magnetic networks, also creates multiple reflection paths for EM waves while preserving the mechanical deformability required for sensing, which serves as a pathway to increase strain response sensitivity and EM loss capabilities [48–50]. These approaches enable conductive networks to maintain sufficient connectivity for EM dissipation while preventing excessive continuity that compromises sensing accuracy, effectively resolving material-level contradictions. Furthermore, by thoroughly considering the impact of varying deformation levels on the sensing and EM absorption properties during material design, truly deformation-compatible sensing–absorption materials may be developed. Examples include hierarchical porous structures with multiscale pores [43,51], in which the pores provide the deformation space required for sensing while maintaining excellent EM absorption capabilities during deformation. Additionally, layered multifunctional materials [52] can be incorporated to minimize the deformation of the absorber during sensing, thereby ensuring stable EM absorption performance. In the future, we can further leverage machine learning-assisted decision-making and high-throughput screening modeling to design multifunctional materials that simultaneously exhibit high-performance sensing and outstanding EM absorption properties [53–55].

(2) Collaborative optimization of the sensing-electromagnetic absorbing array architecture. Arrayed structural optimization represents a significant breakthrough direction for enabling macroscale functional programmability in smart aircraft stealth skin (Fig. 2(e)). Through topology optimization algorithms and structure programming techniques, sensor networks and wave-absorbing units can be coupled to form field-responsive arrays. For example, bioinspired topological structures and finite element algorithms can optimize the functional arrangement of sensing nodes and absorber cavities within a unit area [56], thereby increasing the functional efficiency of materials per unit volume. In addition, metasurfaces such as frequency-selective surfaces (FSSs) can be incorporated to control wave reflection/transmission characteristics through structural geometry, enabling adaptation to EM requirements across different frequency bands [53,57]. In the future, integrating metasurfaces onto the surface of the encapsulation layer of smart skins will enable functional zoning within smart aircraft stealth skins. This approach simultaneously fulfills the sensing requirements while ensuring the stability of the EM absorption performance [58]. We believe that optimizing the array structure for sensing and electromagnetic absorption, simultaneously delivering high-performance sensing and broadband stealth, represents a key pathway toward realizing smart aircraft stealth skin in the future [30,54].

(3) Highly integrated manufacturing and systematic flexible construction. As shown in Fig. 2(f), the continuous breakthroughs in process integration and equipment research provide a tool guarantee for the construction and large-scale engineering of smart stealth skin. Currently, emerging technologies such as three-dimensional (3D) printing, flexible electronics printing, and laser engraving processes are gradually achieving the capability to perform coordinated deposition of multiple materials and functional zones [59–61], thereby facilitating the large-area fabrication of metasurface structures and sensor devices. Techniques such as direct writing, aerosol deposition, and inkjet spraying allow precise spatial control of functional components, supporting fabrication from millimeter structures down to nanolevel interfaces [62], which will facilitate preparation of multifunctional composites with multiscale structure. Roll-to-roll flexible printing facilitates the continuous production of circuits and sensors on large-area elastic substrates [63], which is crucial for scalable "smart stealth skin" deployment. Moreover, laser engraving and plasma-assisted embedding enhance interfacial bonding and functional layer compatibility, improving skin encapsulation stability and ensuring system reliability in complex environments [12,13,16]. These advanced manufacturing methods collectively offer high integration consistency and tunable performance, thus serving as essential tools for constructing intelligent, adaptable, and evolvable skin systems. With ongoing breakthroughs in processes that enable the simultaneous achievement of large-area coverage, fine-scale integration, and low-cost mass production, the mass preparation of future smart stealth skins holds significant promise and opportunity.

Therefore, although there are still challenges associated with composite materials, multifield structural design, and system manufacturing, iterative breakthroughs based on new materials, new structures, and new processes have strengthened the theoretical and engineering foundation for the integration of "sensing–EM absorption" function. As shown in Fig. 2(g), the synergistic development of material innovation, structural optimization, and process upgrading can effectively promote the integration of multifunctionality in aircraft skins, including multiparameter environmental sensing, structural condition monitoring, and EM absorption. The in-depth integration of self-sensing and EM absorption will significantly enhance the safety and stability of the aircraft. Continuously deepening research on the synergistic mechanisms of material–structure processes will become key to advancing this field toward practicalization and thus enhancing aircraft performance.

3. Conclusions

The advancement of future aviation equipment will impose greater demands on skin systems, necessitating a shift from discrete function integration to ontological function fusion to meet the complex demands of multimission, multiscenario, and multienvironment adaptability. By continuously pushing the boundaries of materials, structures, and processes and deeply exploring the potential of multifunctional intelligent integrated design, the evolution of aircraft skins will help propel the new generation of aircraft to new heights of technical performance. We believe that with the further development of sensing–absorption fusion technology, future aircraft skins will not only promote comprehensive upgrades in environmental sensing and EM control capabilities but also provide abundant technical inspiration for future multifunctional construction and system design.

CRediT authorship contribution statement

Kun Wei: Writing – original draft, Visualization, Investigation. **Wanheng Zhou:** Writing – original draft, Visualization, Investigation, Formal analysis. **Xiaoke Lu:** Writing – original draft, Supervision, Formal analysis. **Xueyong Wei:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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