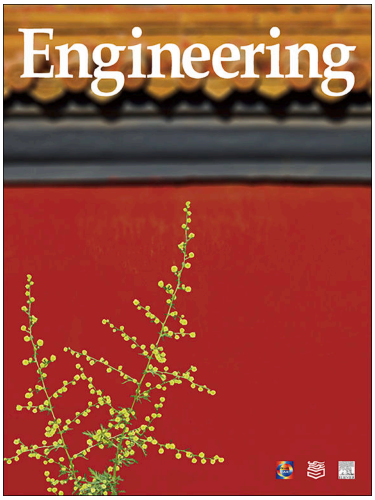

Views & Comments

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

Kun Wei, Wanheng Zhou, Xiaoke Lu, Xueyong Wei

PII: S2095-8099(26)00252-3
DOI: https://doi.org/10.1016/j.eng.2026.04.013
Reference: ENG 2331

To appear in: *Engineering*

Received Date: 11 November 2025
Revised Date: 28 March 2026
Accepted Date: 1 April 2026

Please cite this article as: K. Wei, W. Zhou, X. Lu, X. Wei, Challenges and Opportunities of Smart Aircraft Stealth Skin: Perspectives from Self-Sensing and Electromagnetic Absorption Compatibility, *Engineering* (2026), doi: https://doi.org/10.1016/j.eng.2026.04.013

Views & Comments

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

Kun Wei [a,b], Wanheng Zhou [a,b], Xiaoke Lu [c], Xueyong Wei [a,b,*]

[a] *School of Instrument Science and Technology, Xi'an Jiaotong University, Xi'an 710049, China*

[b] *State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710049, China*

[c] *Frontier Institute of Science and Technology, Xi'an Jiaotong University, Xi'an 710072, China*

* Corresponding author.

E-mail address: seanwei@xjtu.edu.cn (X. Wei)

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.

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 multi-mission, multi-scenario, and multi-environment 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)).

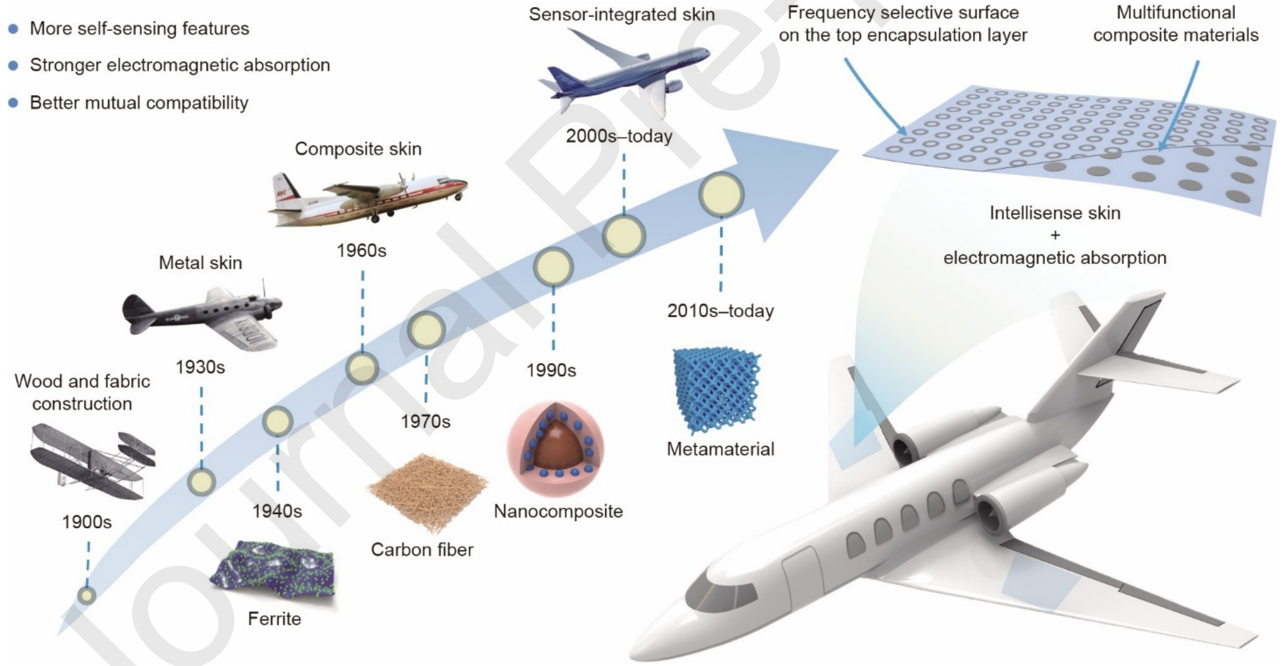

Fig. 1. (a) Brief chronology of the evolution of aircraft skin and electromagnetic absorbing materials, focused mainly on their parallel development. (b) A schematic diagram of smart aircraft stealth skin. In the future, compatibility between self-sensing and electromagnetic absorption functions is expected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

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 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 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.

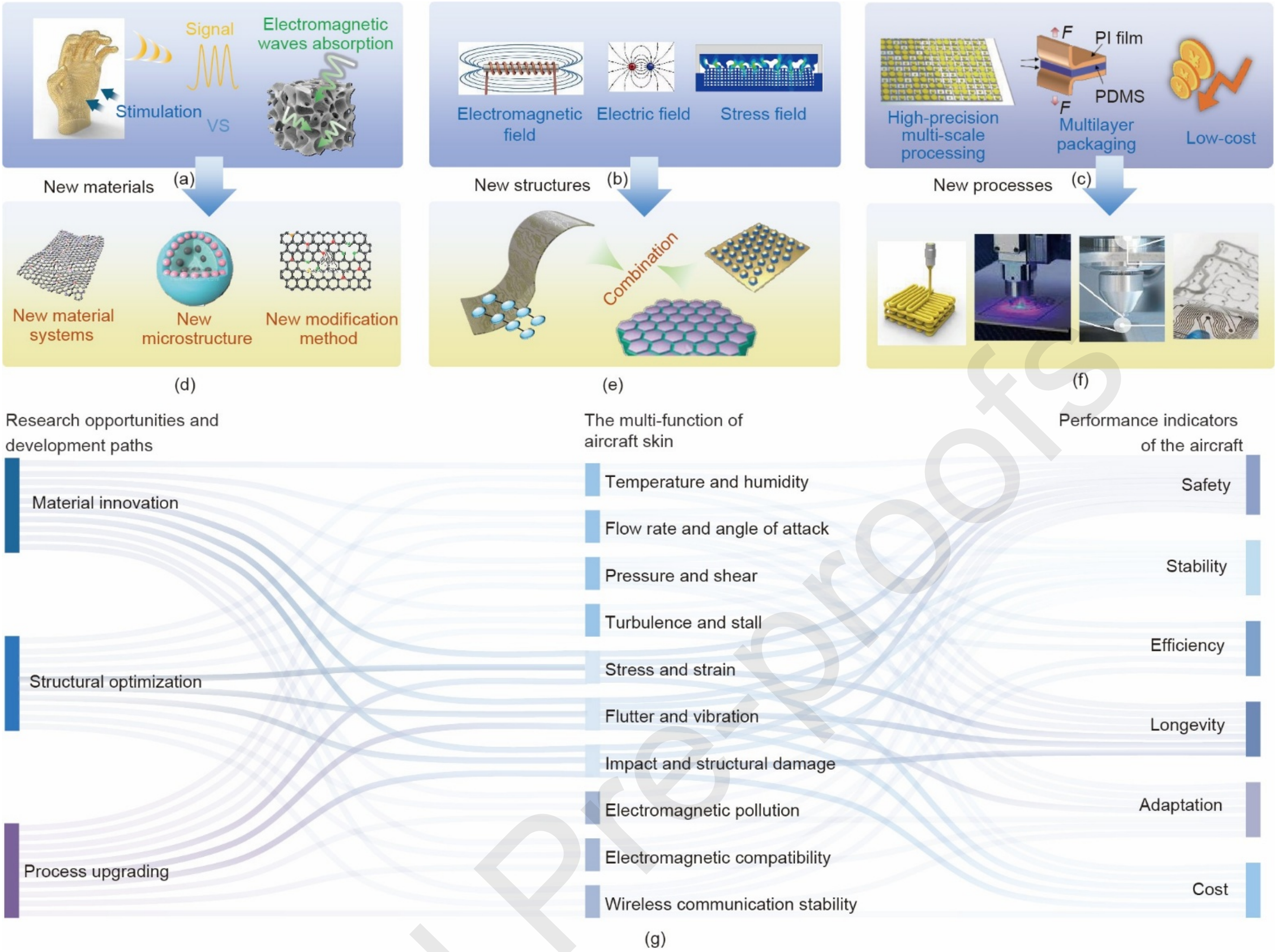

Fig. 2. The challenges and prospects of future aircraft skin. (a) The inherent contradiction of material functional properties. (b) Theoretical and technical bottlenecks in structural optimization design. (c) Immaturity of manufacturing technology and system integration. PI, PDMS and F stands for polyimide, 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.

3. Conclusion

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.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (52402367), the China Postdoctoral Science Foundation (2023M742757 and GZB20230564), the Postdoctoral Research Project of Shaanxi (2023BSHEDZZ80), the Fundamental Research Funds for the Central Universities (xzy012023013), and the Natural

Science Basic Research Program of Shaanxi (2024JC-YBQN-0471).

References

[1] Lopresto V. Crashworthiness design and evaluation of civil aircraft structures. Prog Aerosp Sci 2024;148:101000.

[2] Padfield GD, Lawrence B. The birth of the practical aeroplane: an appraisal of the Wright brothers' achievements in 1905. Aeronaut J 2022;109(1098):421–37.

[3] Ahmad F, Al Awadh M, Noor S. Optimum alternate material selection methodology for an aircraft skin. Chin J Aeronauti 2023;36(7):476–88.

[4] Murugan S, Saavedra Flores EI, Adhikari S, Friswell MI. Optimal design of variable fiber spacing composites for morphing aircraft skins. Compos Struct 2012;94(5):1626–33.

[5] Le VT, Ha NS, Goo NS. Advanced sandwich structures for thermal protection systems in hypersonic vehicles: a review. Compos Part B Eng 2021;226:109301.

[6] Liu YY, Jing ZG, Liu Q, Li A, Teng CA, Cheung Y, et al. Differential-pressure fiber-optic airflow sensor for wind tunnel testing. Opt Express 2020;28(17):25101–13.

[7] Huang YA, Zhu C, Xiong WN, Wang Y, Jiang YG, Qiu L, et al. Flexible smart sensing skin for "Fly-by-Feel" morphing aircraft. Sci China Technol Sci 2021;65(1):1–29.

[8] Kwon H, Park Y, Kim JH, Kim CG. Embedded fiber Bragg grating sensor–based wing load monitoring system for composite aircraft. Struct Health Monit 2019;18(4):1337–51.

[9] Groo L, Inman DJ, Sodano HA. *In Situ* damage detection for fiber-reinforced composites using integrated Zinc Oxide Nanowires. Adv Funct Mater 2018;28(35):1802846.

[10] Jiang S, Shen YP, Wang SL, Jiang W, Liu Y, Wu QZ. Flexible piezoelectric composite sensor for impact monitoring of curved structures. Sens Actuators A Phys 2023;362:114655.

[11] Zhu LQ, Sun GK, Bao WM, You Z, Meng FY, Dong ML. Structural deformation monitoring of flight vehicles based on optical fiber sensing technology: a review and future perspectives. Engineering 2022;16:39–55.

[12] Wang JX, Wei XY, Shi JL, Bai NN, Wan X, Li B, et al. High-resolution flexible iontronic skins for both negative and positive pressure measurement in room temperature wind tunnel applications. Nat Commun 2024;15(1):7094.

[13] Qiu L, Lin XD, Wang Y, Yuan SF, Shi WL. A mechatronic smart skin of flight vehicle structures for impact monitoring of light weight and low-power consumption. Mech Syst Signal Process 2020;144:106829.

[14] Ji JJ, Zhu JF, Niu BY, Lu J, Huang YA. Full-field deformation perception via flexible sensing film integrating modified inverse finite element method. IEEE Trans Instrum Meas 2024;73:7503111.

[15] Wang Y, Hu SG, Xiong T, Huang YA, Qiu L. Recent progress in aircraft smart skin for structural health monitoring. Struct Health Monit 2021;21(5):2453–80.

[16] Xiong WN, Zhu C, Guo DL, Hou C, Yang ZX, Xu ZY, et al. Bio-inspired, intelligent flexible sensing skin for multifunctional flying perception. Nano Energy 2021;90(Part A):106550.

[17] Tariq MR, Ahmad M, Naik M, Khan I, Zhang BL. A comprehensive review of the advancement of transition metal oxide nanocomposites for microwave absorption. Coord Chem Rev 2025;533:216535.

[18] Wang XY, Xing XF, Zhu HS, Li J, Liu T. State of the art and prospects of Fe_3O_4/carbon microwave absorbing composites from the dimension and structure perspective. Adv Colloid Interface Sci 2023;318:102960.

[19] Kim SH, Lee SY, Zhang YL, Park SJ, Gu JW. Carbon-based radar absorbing materials toward stealth technologies. Adv Sci 2023;10(32):2303104.

[20] Tan X, Gu WH, Tao Z, Chen XL, Li SY, Xia AL, et al. Carbon-based materials for radar-infrared compatible stealth technology. Chem Eng J 2025;507:160168.

[21] Lu XK, Li X, Cao YC, Zhu WL, Wang YJ, Ren ZW, et al. 1D CNT-expanded 3D carbon foam/Si_3N_4 sandwich heterostructure: utilizing the polarization compensation effect for keeping stable electromagnetic absorption performance at elevated temperature. ACS Appl Mater Interfaces 2022;14(34):39188–98.

[22] Lu XK, Li X, Wang YJ, Hu W, Zhu WJ, Zhu DM, et al. Construction of $ZnIn_2S_4$ nanosheets/3D carbon heterostructure with Schottky contact for enhancing electromagnetic wave absorption performance. Chem Eng J 2022;431(Part 2):134078.

[23] Lu XK, Zhu DM, Li X, Li MH, Chen Q, Qing YC. Gelatin-derived N-doped hybrid carbon nanospheres with an adjustable porous structure for enhanced electromagnetic wave absorption. Adv Compos Hybrid Mater 2021;4(4):946–56.

[24] Lu XK, Zhu DM, Li X, Wang YJ. Architectural design and interfacial engineering of CNTs@$ZnIn_2S_4$ heterostructure/cellulose aerogel for efficient electromagnetic wave absorption. Carbon 2022;197:209–17.

[25] Wu HJ, Liu JL, Liang HS, Zang DY. Sandwich-like Fe_3O_4/Fe_3S_4 composites for electromagnetic wave absorption. Chem Eng J 2020;393:124743.

[26] Lv HL, Yao YX, Li SC, Wu GL, Zhao B, Zhou XD, et al. Staggered circular nanoporous graphene converts electromagnetic waves into electricity. Nat Commun 2023;14(1):1982.

[27] Li QG, Zhang J, Liu LH, He C, Zhu WR. Graphene-based optically transparent metasurface for microwave and terahertz cross-band stealth utilizing multiple stealth strategies. Carbon 2024;219:118833.

[28] Li WC, Li CS, Lin LH, Wang Y, Zhang JS. All-dielectric radar absorbing array metamaterial based on silicon carbide/carbon foam material. J Alloys Compd 2019;781:883–91.

[29] Qin J, Shi YZ, Jiang SB, Gao YS, Yao SP, Wang ZS, et al. Ultrabroadband and >93% microwave absorption enabled by “doped” water meta-atom lattice with subwavelength thickness. Adv Mater 2024;36(52):2411153.

[30] Chen QK, Zhao SJ, Han Y, Wang YC, Mei DQ, Li Q, et al. Adaptive Metaskins for active and passive thermal camouflage. Adv Mater 2026;38(1):e06934.

[31] Bo YW, Zhang Q, Bai PJ, Cui H, Liu LL, Wang GF, et al. Flexible active pixel-matrix ultrafast thermal camouflage using square-wave temperature. Joule 2024;8(7):2160–9.

[32] Li XL, Sheng XX, Fang Y, Hu XP, Gong S, Sheng MJ, et al. Wearable Janus-Type film with integrated all-season active/passive thermal management, thermal camouflage, and ultra-high electromagnetic shielding efficiency tunable by origami process. Adv Funct Mater 2023;33(18):2212776.

[33] Yang N, Xu CY. An ultrathin polymer-derived UHTCs coating on CFRP substrate: Effective electromagnetic wave absorber. Compos Commun 2023;43:101713.

[34] Liu XM, Liu HQ, Wu HJ, Zhou Q, Liang HS, Liu GQ, et al. Structural electromagnetic absorber based on MoS_2/PyC-Al_2O_3 ceramic metamaterials. Small 2023;19(33):2300664.

[35] Chen WF, Yan X. Progress in achieving high-performance piezoresistive and capacitive flexible pressure sensors: a review. J Mater Sci Technol 2020;43:175–88.

[36] Chen JW, Zhu YT, Huang JR, Zhang JX, Pan D, Zhou JY, et al. Advances in responsively conductive polymer composites and sensing applications. Polym Rev 2020;61(1):157–93.

[37] Ren JF, Huang X, Han RL, Sun YX, Chen GX, Li QF, et al. Ultrahigh-resolution multimodal tactile sensors enabled by multi-scale conductive network construction and band engineering for intelligent perception. Adv Funct Mater 2025;35(52):e12937.

[38] Zhan YF, Xia L, Yang H, Zhou N, Ma GS, Zhang T, et al. Tunable electromagnetic wave absorbing properties of carbon nanotubes/carbon fiber composites synthesized directly and rapidly via an innovative induction heating technique. Carbon 2021;175:101–11.

[39] Chang Y, Wang L, Li RY, Zhang ZC, Wang Q, Yang JL, et al. First decade of interfacial Iontronic sensing: from droplet sensors to artificial skins. Adv Mater 2021;33(7):2003464.

[40] Wu GC, Li X, Bao RR, Pan CF. Innovations in tactile sensing: microstructural designs for superior flexible sensor performance. Adv Funct Mater 2024;34(44):2405722.

[41] Tong W, Song B, Hao L, Xing R, Jun Y, Liu X, et al. Multiscale construction of wave-absorbing carbon nanomaterials. Discov Nano 2025;20(1):107.

[42] Han H, Lou ZC, Wang QY, Xu L, Li YJ. Introducing rich heterojunction surfaces to enhance the high-frequency electromagnetic attenuation response of flexible fiber-based wearable absorbers. Adv Fiber Mater 2024;6(3):739–57.

[43] Yang ZW, Wang JX, Wan X, Xu HC, Zhang CY, Lu XK, et al. Microbubble-based fabrication of resilient porous ionogels for high-sensitivity pressure sensors. Microsyst Nanoeng 2024;10(1):177.

[44] Sengupta D, Mastella M, Chicca E, Kottapalli AGP. Skin-inspired flexible and stretchable electrospun carbon nanofiber sensors for neuromorphic sensing. ACS Appl Electron Mater 2022;4(1):308–15.

[45] Lv HL, Yao YX, Yuan MY, Chen GY, Wang YC, Rao LJ, et al. Functional nanoporous graphene superlattice. Nat Commun 2024;15(1):1295.

[46] Khalid MY, Umer R, Zweiri YH, Kim JK. Rise of graphene in novel piezoresistive sensing applications: a review on recent development and prospect. Mater Sci Eng Rep 2025;163:100891.

[47] Xia YX, Gao WW, Gao C. A review on graphene-based electromagnetic functional materials: electromagnetic wave shielding and absorption. Adv Funct Mater 2022;32(42):2204591.

[48] Chen QC, Xiong YK, Wang YZ, Wang JL, Zhou SH, Sun GH, et al. Architecturally partitioned core-sheath woven fabric for integrated electromagnetic wave absorption and self-powered non-contact sensing. Adv Funct Mater 2025;36(15):e18158.

[49] Wei H, Li WH, Bachagha K. Component optimization and microstructure design of carbon nanotube-based microwave absorbing materials: a review. Carbon 2024;217:118651.

[50] Zhang T, Zhao DC, Wang LJ, Meng R, Zhao H, Zhou PY, et al. A facile precursor pyrolysis route to bio-carbon/ferrite porous architecture with enhanced electromagnetic wave absorption in S-band. J Alloys Compd 2020;819:153269.

[51] Bai Jl, Xie ZC, Zhang PF, Wang SC, Liu ZH, Yao XM et al. Porous $SiCN_{nw}/C/Si_3N_4$ ceramics with controlled component and structure for electromagnetic wave absorption. Compos Part B Eng 2025;294:112164.

[52] Zhao XQ, Zhang PL, Zhang S, Yu W, Wang ZY, Hu N, et al. Breathable, robust, and flexible hierarchical design of multifunctional integrated smart textiles for human health management. Chem Eng J 2025;507:160736.

[53] Lu H, Zhao JW, Zhu PX, Song WJ, Zhu SQ, Zhu RR, et al. Neural network-assisted metasurface design for broadband remote invisibility. Adv Funct Mater 2025;35(45):2506085.

[54] Qian C, Zheng B, Shen YC, Jing L, Li EP, Shen L, et al. Deep-learning-enabled self-adaptive microwave cloak without human intervention. Nat Photonics 2020;14(6):383–90.

[55] Wu B, Qian C, Wang ZD, Lin PJ, Li EP, Chen HS. MetaSeeker: sketching an open invisible space with self-play reinforcement learning. Light Sci Appl 2025;14(1):211.

[56] Li SJ, Pan KC, Du J, Liu ZF, Qiu J. Coral-inspired terahertz-infrared Bi-stealth electronic skin. Angew Chem Int Ed 2024;63(26):e202406177.

[57] Bajaj P, Kundu D, Singh D. Frequency selective surface-based electromagnetic absorbers: trends and perspectives. Wirel Pers Commun 2023;131(3):1881–912.

[58] Huang YH, Li YZ, Pan KW, Fang YX, Chan KC, Xiao XY, et al. A direct laser-synthesized magnetic metamaterial for low-frequency wideband passive microwave absorption. Int J Extreme Manuf 2023;5(3):035503.

[59] Deng KX, Wu HH, Song B, Li Y, Hao JH, Ji YX, et al. 3D-printed conical structure absorber based on NFG/Fe_3Si/SiCnw ternary composites for multifunctional integrated electromagnetic microwave absorption. Compos Part B Eng 2024;274:111243.

[60] Wang YR, Su RY, Chen JQ, Wang WQ, Zhang XQ, Xu H, et al. 3D printed bioinspired flexible absorber: toward high-performance electromagnetic absorption at 75–110 GHz. ACS Appl Mater Interfaces 2023;15(46):53996–4005.

[61] Kamat AM, Pei YT, Kottapalli AGP. Bioinspired cilia sensors with graphene sensing elements fabricated using 3D printing and casting. Nanomaterials 2019;9(7):954.

[62] Pratap A, Rajabi Kouchi F, Burgoyne H, Curtis M, Rektor A, Seol ML, et al. Direct writing of PVBVA/$Ti_3C_2T_x$ (MXene) triboelectric nanogenerators for energy harvesting and sensing applications. Nano Energy 2025;142(Part A):111206.

[63] Li JQ, Li M, Chen ZF, Shao SS, Gu WB, Gu Y, et al. Large area roll-to-roll printed semiconducting carbon nanotube thin films for flexible carbon-based electronics. Nanoscale 2023;15(11):5317–26.

Compliance with ethics guidelines

Kun Wei, Wanheng Zhou, Xiaoke Lu, and Xueyong Wei declare that they have no conflict of interest or financial conflicts to disclose.