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Functionalized composite structures for new generation airframes: a review

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Abstract

The uncontroversial superiority of functionalized composite structures for new generation airframes has been well acknowledged by the research community. Such an approach has the potential to substantially enhance system performance and reduce overall manufacture–operation–maintenance expenditure. Recent progress in informatics and high-capability computing devices has offered a brand-new springboard for the aerospace community to reshuffle its traditional R&D criteria for functionalized composite structures. Particularly, artificial intelligence (AI), an intriguing information processing technique, exhibits outstanding effectiveness in accommodating the highly demanding requirements of new generation airframes. Appropriate utilization of AI techniques in functionalized composite airframe design will contribute to the realization of high-capability intelligent systems.

The applications of advanced composite structures, artificial intelligence and sensing network techniques in aircraft industry are briefly reviewed in this paper, in correlation with various novel concepts. As a specific case study, an AI technique-based composite structure with the capability of structural health monitoring was developed. An artificial neural network was customized and trained using digitized spectrographic characteristics extracted from a multi-point sensing network. The system was then validated by executing on-line health diagnostics, and the results indicate excellent performance of AI techniques in functionalized composite structures.

Keyword: Composite structure

1. Introduction

A challenging issue presented in the aircraft community is how to substantially enhance the performance of engaged materials and structures so as to strengthen their integrity and reliability, and meantime lower manufacture–operation–maintenance cost. Owing to excellent and unique mechanical properties, composite structures have offered a promising solution to this concern since they were introduced, and have exponentially pervaded into various commercial applications, serving as an attractive candidate to realize current and future trends of new generation aero-vehicles [1,2].

Biomimetics, developed since last decade, has functioned as a brand-new springboard for engineering communities to reshuffle their traditional R&D principles. Biomimetics literally means imitation of life, and more practically this concept refers to an interdisciplinary effort aimed at understanding biological principles and then applying them to improvement of existing technologies or creation of entirely new technologies [3]. As one realization of biomimetics, artifi-

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cial intelligence (AI), a novel information processing technique emerged in the mid-1950s, is reputably capable of learning, perception, and ratiocination. Such a technique can be used to deal with a wide variety of complex scientific and engineering problems. At present, applications of AI technique in the aircraft industry range from material design, manufacture, aircraft maneuver, combat training, to traffic control and damage detection [4].

Combination of the two above-mentioned intriguing technologies stimulates the concept of AI-inspirited functionalized composite structures. It is anticipated, via such a principle, to achieve essential improvement in integrity, reliability, performance, testability, robustness and cost effectiveness of new generation aircraft.

The status of on-going research and applications of advanced composite structures and AI techniques, as well as sensing networks, in aircraft industry is briefly reviewed in this paper. As a specific application, a functionalized carbon fibre/epoxy composite structure featuring AI-supported structural health monitoring (SHM) capability is introduced with validation. In this system, an artificial neural network (ANN) is designed and trained with signal spectrographic characteristics extracted from a multi-point sensing network.

2. Composite materials and structures in airframes

2.1. Historical retrospect

Since patented by the DeHavilland Aircraft Co. in the 1930s [5] and probably first introduced into commercial use as fuselage skin for Vultee BT-15 trainer plane in 1944 [6], composite materials have been increasingly employed by aeronautic and astronautic industries. Based on matrix materials, the composites employed in aircraft can be roughly categorized as polymer–matrix, cement–matrix, metal–matrix, carbon–matrix and ceramic–matrix composites [7], where the material embedded in matrix behaves as the key structural properties, while the matrix serves as the binder to shape a structural entity. Due to the superb strength-to-weight and stiffness-to-weight ratios, substantial weight saving and performance improvement can be achieved through the utilization of composite materials compared with conventional counterparts such as aero-aluminium alloy [6]. For instance, 40–60% weight reduction is expected by using high-strength titanium alloys and metal matrix composites (MMCs) with oriented continuous fibre reinforcement for early-21st-century aircraft [8]. Allied to advantages in mechanical properties, their excellent thermal, electric and magnetic features are also favorable for aircraft flutter suppression [9], fatigue-crack reinforcement and repair [10,11], debris prevention [12,13], temperature resistance [14], and damage detection [15–20]. By way of illustration, applications of composite materials in some typical commercial and military aircrafts are summarized in Table 1 [24], while detailed reviews of their applications can be referred to elsewhere [21–23].

2.2. Future visions of boeing and airbus

Targeting safety-essence, cost-efficiency, airworthiness, system integrity, commonality and environmental compatibility, major aircraft manufacturers are now

Table 1
Application of composite materials in some typical aircraft [24]

Aircraft (military)	Composite components	Aircraft (commercial)	Composite components
C-17	Large tail cone, winglet skins, fairing, etc.	Boeing 737	Aileron, elevator, rudder control surface, etc.
AV-8B	Wing trailing edge, wing skin, flap, aileron, etc.	Boeing 747	Fairings, nacelle components, winglet, etc.
F-15	Horizontal and vertical tail skin, speed brake, etc.	Boeing 757	Control surface, landing gear door, thrust reverser, block doors, etc.
F-16	Horizontal and vertical tail skin, control surface, etc.	Boeing 767	Empennage, exterior surfaces, horizontal stabilizer, etc.
F-22	Wing, fuselage, empennage, forward-fuselage frame, etc.	Boeing 777	Rudder, fuselage side panel, stabilizer, control surface, etc.
F/A-18 E/F	Fuselage skin, wing skin, etc.	Airbus 300	Radome, pylon fairings, wing cover panels, etc.
Eurofighter aircraft (EFA)	Monocoque, cured frames, longerons, wetted area, etc.	Airbus 310	Pylon fairings, fin leading, rudder, apron, spoiler, etc.
Advanced jet fighter (AJF)	Vertical tail stabilizer, etc.	Airbus 320	Stabilizer, fin, horizontal tailplane, etc.
Joint strike fighter (JSF-F35)	Fuselage skin, upper wing skin tails, control surface, inlet duct, engine access cover panel, etc.	Airbus 330	Flaps, empennage, floor beam, pressure bulkhead, control lever, etc.
AH-64A	Lower leading-edge fairings, stabilator, etc.	Airbus 340	Flaps, empennage, cockpit furnishings, control lever, etc.

actively involved in the research and development of innovative functionalized materials and structures for the next generation aero-vehicles.

As the biggest commercial aircraft supplier worldwide, Boeing Co. recently publicized its new generation super-efficient commercial aircraft Dreamliner B-7E7, which will allow future airlines to transport passengers with the most economical operation cost. Competitively, Airbus also launched its ambitious program, the A380 project, in 2000. This jumbo is claimed to be the most advanced, spacious and efficient transportation vehicle that human beings can conceive.

These two masterpieces are being individually developed, based on Boeing's and Airbus's divergent anticipations of future commercial transportation operation, reflecting their unique visions for the crucial market of competition. However, one mutual feature of both jets is the unprecedented consumption of composite materials. Dreamliner B-7E7 will be the first commercial aircraft in which the majority of its structures, including fuselage and wings, will be made of lightweight, superstrong blends of carbon fibres and epoxy [25,26], compared with the utility of 11% in its latest jet B-777. Such a measure contributes to at least 3% fuel saving. Under the exclusive structural design criteria proposed by Airbus, as schematically shown in Fig. 1, 22% of the components of A380 will be manufactured using composites (Fig. 2 [27]). Additionally, A380 will be the first large commercial aircraft with the CFRP composite centre wing box. It boasts a weight saving of up to one and a half tonnes compared to other aircrafts using the most advanced aluminum alloys.

Such massive consumption of composite materials motivates innovations in material manufacturing. Airbus introduces the latest manufacturing technologies for A380, including automated fibre placement (AFP), automated tape laying (ATL), resin film infusion (RFI) and resin transfer moulding (RTM). Based on these, the novel concepts of GLARE and laser beam welding (LBW) are established for the jumbo. Impregnated with an epoxy adhesive, GLARE is a kind of hybrid material built up from alternating slight overlap layers of aluminum foils with unidirectional glass fibres, leading to a single or double curved skin to obtain local reinforcement. It is estimated that the application of GLARE will lead to remarkable improvement in resistance to corrosion and fire. The adoption of LBW, by replacing the traditional riveting process for stringers of lower fuselage panels, is aimed at reducing crack growth in the aircraft skin [27].

3. Artificial intelligence and its applications in aircraft industry

Defined as the simulation of human intelligence so as to efficiently use 'knowledge' at a given step toward solving a problem [28], AI serves as a powerful solution to complex engineering problems, for which conventional straightforward logical algorithms are usually inefficient. At this stage, several variants originating from fundamental AI concept can be found in applications, namely expert system (knowledge-based system), fuzzy logic, inductive learning, genetic algorithms and artificial neural network.

In particular, expert system and neural network are most efficient. Basically, an expert system contains the knowledge database for solving a particular kind of problem by means of explicit 'IF–THEN' rules [4]. Though promising, most expert systems are unwieldy in their re-

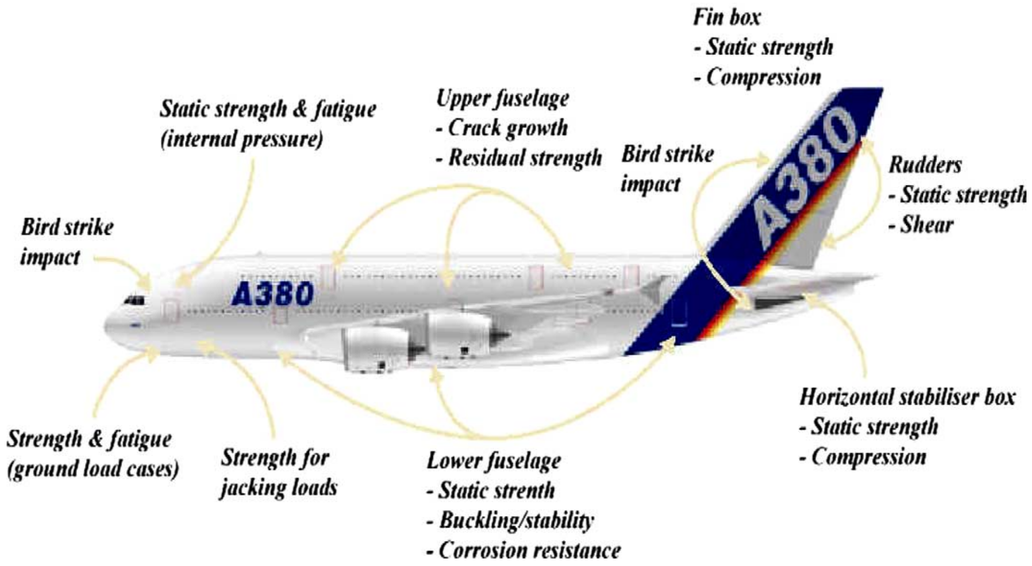

Fig. 1. General design criteria for A380 fuselage and empennage [27].

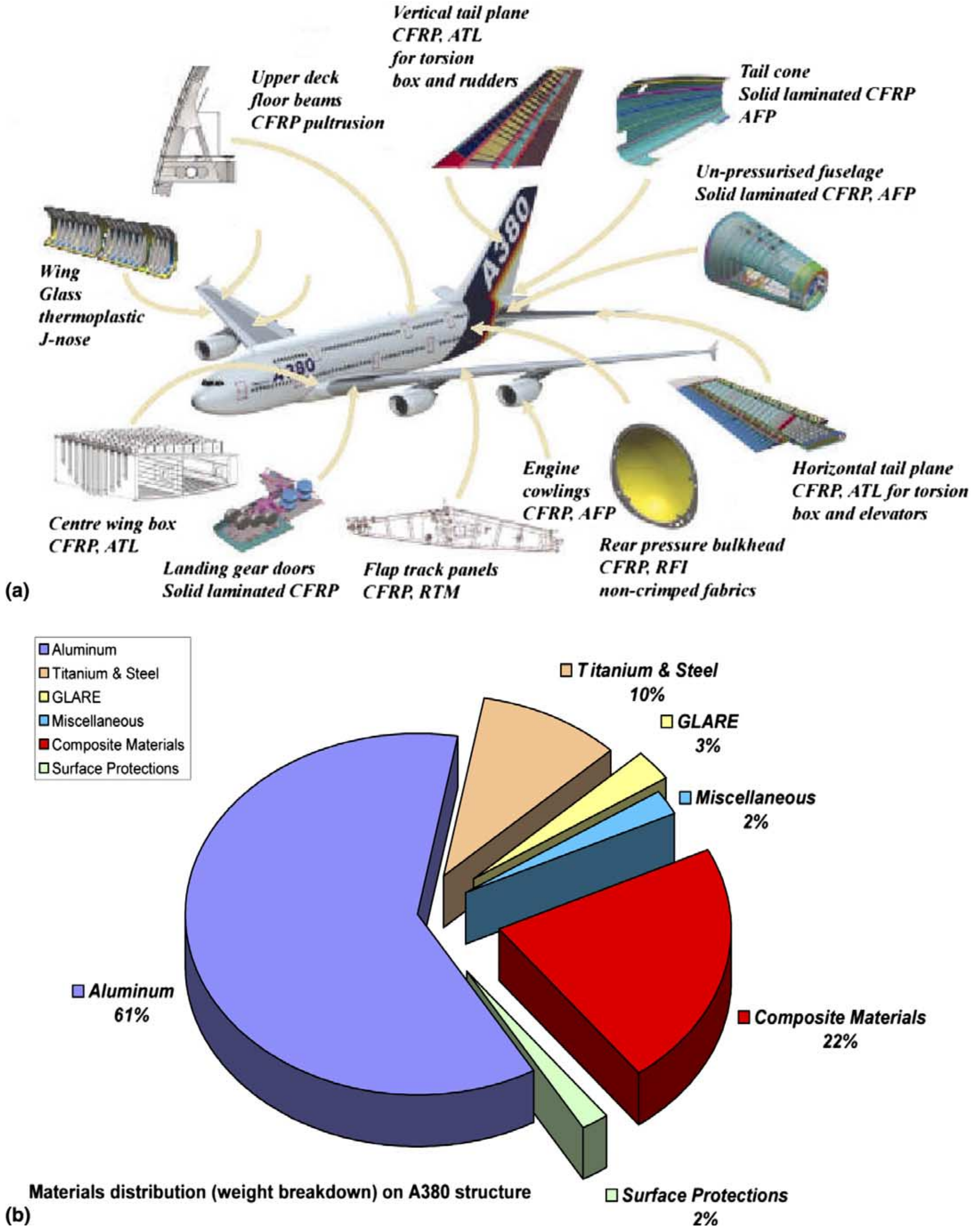

Fig. 2. Utility of composite structures on A380: (a) monolithic CFRP and thermoplastics; (b) materials distribution (weight breakdown).

sponse to new stimulants that are not included in their database. With a similar mechanism but beyond the capability of an expert system, artificial neural network (ANN) can be trained using a series of typical inputs and their corresponding expected outputs, to establish an implicit non-linear and multi-dimensional correlation between them while avoid exploring the constitutive relation for a complicated system. Inherently endowed with talents in adaptability, robustness and parallelism, the ANN technique has found substantial applications in pattern recognition, classification, function approximation, signal processing and system identification.

More recently, AI has been accepted for developing control systems for both military fighters and commercial jetliners [29–31]. In such approaches, massive data for various flight conditions, preliminarily obtained from experiments, numerical simulations or actual tests, are hosted in a database and used to train the ANNs. These well trained networks are able to automatically adjust flying parameters to cater for unpredicted environments. Such an AI-based flight control system is also termed as fault tolerant flight control system (FTFCS) in some studies, since it is valid even when some sensors and actuators fail or new conditions appear [32]. The approach is distinctly beneficial to tactical guidance and survivability analysis, capable of keeping the vehicle in a perfect operating condition all the time [33,34]. One of the most successful paradigms using this concept is the unmanned air vehicle (UAV) with an inertial navigation system (INS) [35,36].

Zhang and Friedrich [37] systematically reviewed the applications of neural network technique for composite materials and structures, from fatigue prediction, wear simulation, to manufacturing process monitoring and curing analysis. It is concluded that a well trained ANN is expected to be very helpful in predicting material properties before manufacturing/testing the actual composites, and in simulating the relationships between various manufacturing parameters and material performance. In particular, these predicted results can be used as a basis for a computer-based processing optimization to design new composite materials with reduced need for experiment. Other relevant applications of ANN include traffic control, transport management, airport infrastructure [38–42] and composite manufacturing [43–46].

4. AI technique-supported functionalized structures

4.1. Future vision

As one of the long-term goals for engineering community, ageless aircraft with built-in intelligent self-diagnosis, self-control and self-healing/adjustment/compensation capabilities can serve as a solution to various issues, such as operation safety and life-cycle cost [47].

In an inspiring vision, the research team in NASA has put forward a novel Darwinian vehicle design concept (survival of fittest aircraft) based on AI principles [48]. It is hypothesized that only those aircraft designs that acclimatize best to commercialization (more evolvable, more resilient and more adaptive) can survive. Within this concept, aircraft design and manufacturing adaptively undergo modifications in terms of variable environmental circumstances, thereby ensuring continuous improvement in vehicle functionality yet without the necessity of human intervention [49]. Under Darwinian vehicle design concept, aircraft feature automatic configuration of wing shape and operation control, in which new control algorithms, software and even hardware-configurations can be remotely uploaded from central control on ground to in-service aircraft via a wireless network. It instantly adjusts on-board memory, bandwidth, power, control features and flight software codes. Parallely, updated flight information can also be real-time downloaded from aircraft to central control, to upgrade future design, which can be considered as spiral and reciprocal interactions.

4.2. Self-structural health monitoring

More practically as an achievable short-term target in relation to current efforts, airframes, primarily made of advanced structures integrated with robust sensing systems and intelligent data-processing ability, have come into existence, comprehensively syncretising self-health-prognostics and self-rehabilitation capabilities with structural functionalities.

Advanced structures in aero-vehicles can suffer from abrupt external impacts or extension of internal defects during service, potentially leading to catastrophic failure of aircraft without timely detection and repair. Disastrous disassembly of China Airline CI611 flight (B747-200B) on 25th May 2002 and Columbia space shuttle tragedy on 1st February 2003 entailed 225 and 7 lives lost, respectively. However, these events represented only 15% of total aviatic casualties in 2002 and 2003 [50]. Investigation showed that both catastrophes could be attributed to continuous deterioration of initially non-lethal damage under fatigue or thermal loadings [48,50].

Motivated by aviation safety, on-line SHM is a system with the capability of detecting and interpreting adverse 'changes' in a structure in real-time, so as to enhance reliability and reduce life-cycle costs [51]. A reliable on-line SHM system should possess automatic data acquisition and processing, structural condition assessment, and decision-making for corrective actions. However, as a complicated non-linear inverse problem, SHM is difficult to achieve with most existing logic methods [52].

Recent studies [53–59] have substantiated that the ANN technique is an encouraging solution towards this problem. In practice, various structural characteristics associated with damage in the single time or frequency domain, or static parameters, are normally employed for network training due to their simplicity of capture for damage identification. These parameters include mode shape [55,56] and natural frequencies [53,57], or combined modal information [60]; displacement [61], acceleration spectra [62] or combined parameters of displacement, velocity and acceleration [63]; applied force [64], or static parameters such as strain [65,66], strain history [67], auto-correlation function [68], impedance [69], etc. Subsequent work [70] has also demonstrated that a well-trained ANN exhibits considerable tolerance and robustness for partially incomplete or noise-impaired information. Such a characteristic is particularly beneficial for the health surveillance of flying aircraft, where environmental interference may severely affect the acquired signal or where data acquisition cannot be completely fulfilled.

4.3. Active sensor network

In practice, the acquisition of structural parameters and the implementation of control/compensation are realized through sensors and actuators embedded in or bonded on the structures. Rather than a complicated sensing/actuating network, simple diagnostic sensors have already been widely adopted as standard equipment for most aircraft, to monitor working condition parameters such as temperature, pressure and emissions. However, these sensors can perform only local data acquisition and are effective for specific components or parameters only. As an innovation, Boeing asserts that a high performance sensing network involving diverse sensors will be installed on the Dreamliner B-7E7, capable of automatically and continuously surveiling vehicle performance in real-time. Primary advantages of such a technology are cost-saving and significant extension of service life.

Sensor or sensor network technology, an interdisciplinary subject, is seen as an integrated element in the overall development of functionalized structures, spanning areas of physics, chemistry, materials, molecular biology, fabrication, electronics and signal processing. Basically, sensing devices for current and next generation aircrafts must meet requirements of (1) endurance for general environmental injury, (2) long life for at least 5–10 years, and (3) simple and easy handling and attachment [71]. For higher performance, they should be characterized by smaller size, lighter mass, higher sensitivity, lower cost/power consumption, higher reliability and quicker response to sudden changes, as well as easier integration. To accommodate future aero-applications, remote control and data transmission, toughness for vibration and noise, little aging deterioration and less wire or even wireless network layout are also preferred.

Over the past decades, smart sensor networks and technologies have been well developed in relation to MEMS, nanotechnology, microelectronics, communication networks and distributed computing, multi-functional structures integrated with a built-in smart sensing network, and relevant intelligent signal processing software packages. Various sensing devices are used for different applications. Piezoelectrics, optical fibre, electro-rheological fluids, shape memory materials, and magnetostrictive/electrostrictive materials are some typical examples in the field of aerospace applications. Amongst these, piezoelectrics shows a particularly good capacity to satisfy exigent applications, due to unique mechanical strength, wide frequency response range, and favorable costs. A number of piezoelectric films/patches can be easily distributed yet with only minor effects on the structure's overall mechanical performance. Furthermore, with the aid of advanced encapsulation technology, adaptive thin patches with PZT wafers have been manufactured [72]. This technique is characterized by a wide adaptability concerning shape and materials to meet the requirements of a great variety of applications. The intention of this approach is to prepare and encourage the establishment of adaptive structures of space applications. A first step to adopt this technology to prototype structures has been achieved by the development of special encapsulated patches for an adaptive satellite mirror.

Attached on plate-like structures, such as skins of wing or vertical fin, piezoelectrics can be used to generate stress waves, i.e. Lamb waves. Such a plate wave can propagate over a relatively long distance, even in materials with high attenuation ratio, such as CF/EP composites, and thus monitoring over a broad area can be conducted with only a few transducers in a distributed configuration, saving considerable testing time and costs. Meanwhile, the entire thickness of the plate can be interrogated in virtue of different propagation modes of Lamb waves, affording the ability to detect internal damage as well as defects on skin surfaces [73].

Though there is still a great distance from laboratory research to practical application, as a valuable step, two representative sensor network techniques, SMART Layer® and HELP layer®, are well acknowledged and have demonstrated potential for a wide diversity of engineering cases.

SMART Layer® (also nominated as Stanford Multi-Actuator–Receiver Transduction Layer), developed by a

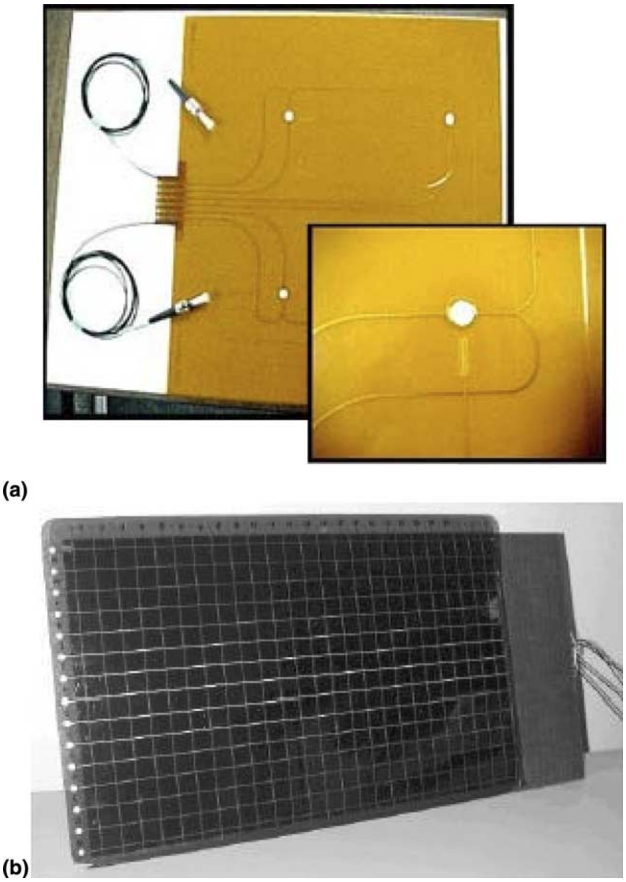

Fig. 3. Commercialized sensing networks, (a) SMART Layer®; (b) HELP layer®.

research team in Stanford University and commercialized by Acellent® Technologies, Inc. [74,75], integrates a certain number of distributed piezoceramics into a dielectric film to configure a network, as shown in Fig. 3(a). As an extra thin and flexible ply fabricated by a printed circuit technique, a SMART Layer® can be either inserted into structure or bonded onto surface to function as an active sensor network, without noticeable degradation of host structural integrity.

Different to SMART Layer® that generates and measures the stress wave, HELP layer® (Hybrid Electromagnetic Performing Layer), in Fig. 3(b), developed by the French Aeronautics and Space Research Center (ONERA), is based on the interaction between electromagnetic field and structural abnormality. Such a layer allows the detection of local variations of electric conductivity and dielectric permittivity induced by damage. Mechanical damages, as well as thermal defects, can be diagnosed due to their evident influence on electromagnetic properties [76].

5. Case study

As a case study for elucidation, a functionalized CF/EP composite structure with artificial neural algorithm-supported SHM capability, developed at the Laboratory of Smart Materials & Structures (LSMS) of the University of Sydney, is here presented.

In practice, aircraft components can be in various geometries. The traditional or even optimized transducer allocation design cannot expediently provide an efficient solution, where the distribution of actuators/sensors and signal excitation/acquisition must be individually considered upon each application. An active sensor network technique was accordingly established to simplify the transducer network design. Four PZT disks were collocated to encircle a square area of 172.5 mm × 172.5 mm and controlled by a signal excitation/acquisition circuit, as illustrated in Fig. 4(a), defined as a standard sensor unit (SSU). Serving as the basic component in an active sensor network, the SSU is collocable. Based on this concept, diverse sensor networks can be conveniently tailored by assembling a set of SSUs to flexibly accommodate different geometries and boundary conditions. The distributed multi-sensor architecture has also been experimentally validated as effective in enhancing the signal-to-noise ratio (SNR) [58], and exhibiting better robustness and reliability in a noisy environment. As an example, an active sensor network involving certain SSUs for a non-regular geometric identity is configured and displayed in Fig. 4(b).

An Intelligent Signal Processing & Patterns Recognition (ISPPR) package, inspirited by an artificial neural algorithm and wavelet transform technique, was developed. Previous studies [77,78] have revealed that structural damages can be quantitatively characterized by energy spectra of the Lamb wave in structures under inspection, which intuitively illustrates damage-scattered Lamb waves over a dual-parameter space (time-frequency domain). A novel concept was introduced in this package to facilitate data processing, where the extracted spectrographic characteristics for each actuator–sensor path in the active sensor network were digitized and stored, referred to as 'digital damage fingerprints' (DDF), uniquely for the actuator–sensor path under current damage situation [79]. By such an approach, a set of DDF can be obtained via all concerned actuator–sensor paths, exclusively for a single damage case. A multi-layer feedforward artificial neural network supervised by an error-backpropagation (BP) algorithm was constructed, in Fig. 5, and trained using the DDF for various damage cases. Via the neural network, the correlation between a structural damage case and DDF was mapped, readily for further prognostics and diagnostics.

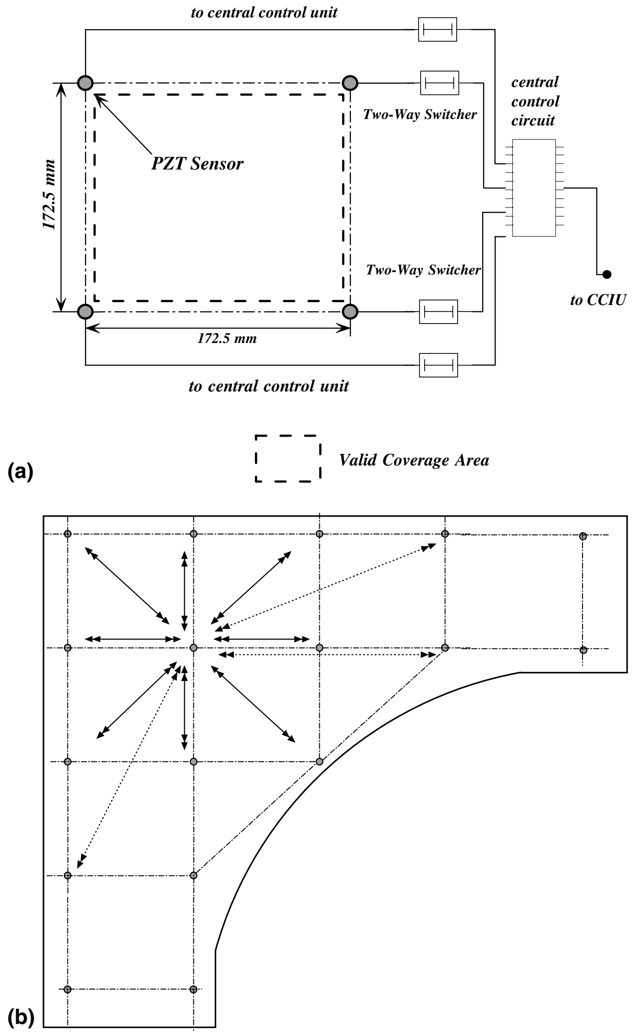

Fig. 4. Active sensor network: (a) standard sensor unit (SSU); (b) customized sensing network for a geometrically non-regular structure.

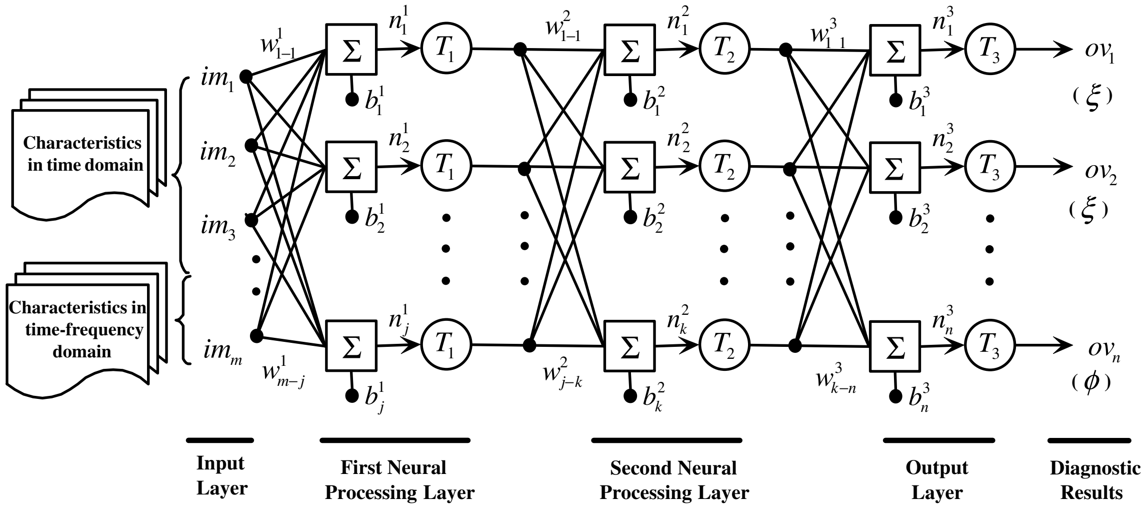

Fig. 5. Artificial neural network for designed functional composite structure.

A quasi-isotropic CF/EP composite laminate in the configuration of $[45/-45/0/90]_s$ was selected as the structure to host the SHM functionalities. During development, a customized actuating/sensing network with programmed control circuits was incorporated onto the composite laminate, to perform monitoring with the aid of ISPPR [79]. Validation of such a system was conducted by on-line evaluating a through-hole damage or delamination in composite laminates (475 mm × 475 mm × 1.275 mm), as shown in Fig. 6. Damage

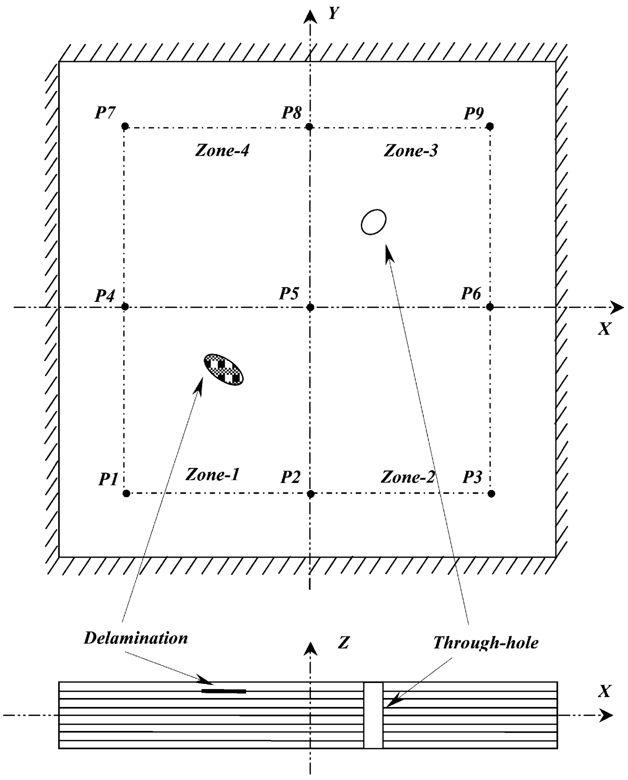

Fig. 6. A CF/EP composite laminate for validation of the technique.

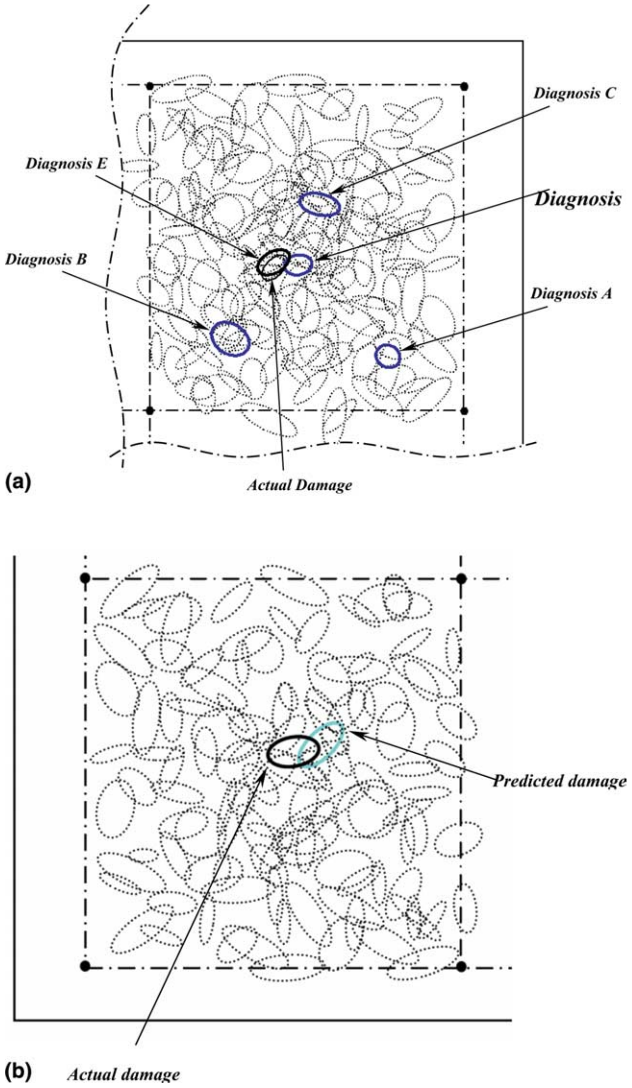

Fig. 7. Damage prediction results: (a) hole-type damage detection; (b) delamination damage detection (⬭, damage patterns for ANN training).

diagnostic results, graphically described in Fig. 7, indicate that satisfactory damage assessment for the composite structure has been achieved [70].

6. Concluding remarks and prospect

The research and application status for advanced composite structures, AI technology, and sensor/sensing network technique, as well as their mutual integration, are concisely addressed in terms of new generation airframes. A functional composite system with built-in SHM capacity is presented as a case study, and the validation exhibits promising prospect of AI technique-inspirited functionalized composite structures for practical applications.

Stringent requirements from new generation cost-efficient aero-vehicles have imposed unprecedented challenges to the community, and have dramatically motivated research and development for novel and practical techniques. In particular, the introduction of bio-technology-based techniques shows encouraging prospects in this field and claims an essential role in the new millennium. Multi-functional structural systems, comprising advanced composites and incorporating bio-technology, will have a great impact on performance enhancement, cost reduction and life extension.

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