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Development, modeling and application of piezoelectric fiber composites

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Abstract: Piezoelectric materials are capable of actuation and sensing and have been used in a wide variety of smart devices and structures. Active fiber composite and macro fiber composite are newly developed types of piezoelectric composites, and show superior properties to monolithic piezoelectric wafer due to their distinctive structures. Numerous work has focused on the performance prediction of the composites by evaluation of structural parameters and properties of the constituent materials with analytical and numerical methods. Various applications have been explored for the piezoelectric fiber composites, including vibration and noise control, health monitoring, morphing of structures and energy harvesting, in which the composites play key role and demonstrate the necessity for further development.

Key words: piezoelectric; active fiber composite; macro fiber composite; modeling; smart applications

1 Introduction

Over the past few decades, the development of smart materials and structures is a rapidly emerging field. There are a variety of smart materials, such as shape memory alloys [1,2], electrostrictives [3], magneto-strictives [4,5] and piezoelectrics [6,7]. Each of these materials can convert one type of input field into another output form. Of these smart materials, piezoelectric materials receive the most interests. Monolithic piezoceramic wafer is a typical piezoelectric material and commonly used in many actuation and sensing applications. The electrical field can be applied via the surface electrodes, normally through the wafer thickness, and high stiffness and bandwidth offer piezoceramics high actuation capability. However, there are disadvantages which limit the applications of monolithic piezoceramics in reality [8]. Piezoelectric ceramics are vulnerable to accidental breakage during handling and bonding procedures due to their inherent brittle nature, and are difficult to conform to curved surfaces due to their stiff mechanical properties. It is therefore impractical to use monolithic piezoceramics for controlling over thin membranes and objects with curved or irregularly shaped surfaces, and for obtaining large deflections required in shape changing applications. The additional mass is another factor limiting their applications in flexible or lightweight structures. Instead piezoelectric polymer is flexible and robust to damage, however, poor actuation capability limits its applications.

These limitations have motivated researchers to develop new types of piezoelectric material for wider applications. Piezoelectric fiber composites with a novel structure consisting of piezoceramic fibers embedded in polymer matrix were developed to remedy the aforementioned restrictions of piezoceramics. Of these piezocomposites, active fiber composite (AFC) and macro fiber composite (MFC) are particularly attractive. In this paper, an overview of recent progress in the development of the piezoelectric fiber composite was given, in aspects of the unique structures, performance prediction and recent progress of applications of AFC/MFC.

2 Development of piezoelectric materials

2.1 Piezoelectric materials

Since the piezoelectric effect was discovered by Pierre Curie and Jacques Curie in 1880, piezoelectric materials have evolved into several forms such as ceramic, polymer and composite. Piezoceramics are the

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most widely used piezoelectric materials. To date, lead zirconate titanate ($Pb(Zr,Ti)O_3$, PZT) based piezoelectric materials are still the most versatile and the most widely used piezoceramics. PZT is a solid solution of lead zirconate ($PbZrO_3$) and lead titanate ($PbTiO_3$), and has a perovskite crystal structure (ABO_3) in which Zr^{4+} and Ti^{4+} ions occupy the body centre at random, Pb^{2+}ions occupy the corners, and O^{2-} ions occupy the centers of each face, as shown in Fig. 1, exhibiting excellent piezoelectric properties because of its anisotropism. Above the Curie point the unit cell is cubic with no piezoelectricity. When cooling below the Curie point, the cubic structure transforms to either rhombohedral or tetragonal, and simultaneously, a spontaneous polarization occurs with a small relative shift of the body center site cations [9]. The lack of a centre of symmetry in the unit cell is the origin of the piezoelectric behavior. Moreover, PZT shows superior dielectric and piezoelectric properties when the compositions are close to the morphotropic phase boundary (MPB) between tetragonal and rhombohedral phases at the Zr:Ti ratio of 52:48 [10]. Modified PZT with piezoelectric coefficients d_{33} as high as 779 pC N^{-1} and Curie temperatures in the range of 300−400 °C had been reported [11]. This high ferroelectric Curie temperature could allow operational temperature of PZT as high as approaching Curie temperature with excellent thermal stability. Additionally, a wide variety of dopants were used to manufacture a range of ‘hard’ and ‘soft’ PZT tuned for specific applications [12].

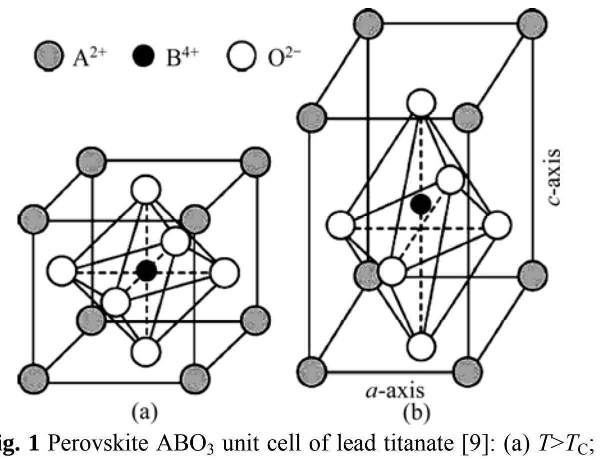

Fig. 1 Perovskite ABO_3 unit cell of lead titanate [9]: (a) $T>T_C$; (b) $T<T_C$

However, the evaporation of toxic lead and its compounds during high-temperature sintering of PZT causes environmental pollution and health hazard. It arouses a general awareness for the development of environmental friendly lead-free materials. Another motivation is the need for piezoceramics suitable for higher temperature operations. Many lead-free piezoceramic materials have been actively explored, mostly based on the perovskite, tungsten-bronze, and bismuth layered structures [13,14]. Despite tremendous recent progress, there is no equivalent substitute for PZT possessing both high piezoelectric coefficients and thermal stability. Moreover, the processing, properties and applications of lead-free piezoceramics under different conditions of stress, frequency, and temperature were not well understood compared to PZT systems.

2.2 Piezoelectric composites

Along with the effort to further improve the piezoceramic’s properties via conventional compositional control, a novel approach of structural arrangement has been developed rapidly. Piezocomposites composed of piezoceramics and polymer were promising materials because of their excellent tailorable properties. NEWNHAM [15] introduced the concept of connectivity for describing the number of dimensions that each phase was physically in contact with itself. According to the connectivity of each phase, the geometry for two-phase composites can be classified into 10 structures, i.e., 0-0, 0-1, 0-2, 0-3, 1-1, 1-2, 1-3, 2-2, 2-3 and 3-3. In the case of piezocomposites, the first number in the notation denotes the physical connectivity of the active phase and the second number refers to the physical connectivity of the passive phase. A schematic of these different connectivities is shown in Fig. 2 [16].

The composites with 1-3 connectivity are the most studied and utilized of all the two-phase connectivity types. This composite consists of individual piezoceramic rods or fibers aligned in a direction parallel to the poling direction and surrounded by a polymer matrix. 1-3 piezocomposites possess many advantages over monolithic piezoceramics, including high coupling factors, low acoustic impedance, mechanical flexibility, and broad bandwidth. These merits make 1-3 piezocomposites the best candidate for ultrasonic transducer applications, taking advantage of low acoustic impedance for good matching to water or human tissue, and broad bandwidth in combination with a low mechanical quality factor and the possibility of making undiced arrays by simply patterning the electrodes [17,18]. Furthermore, many attempts have been made to develop novel configurations and processing techniques for piezocomposites and their applications. Two 1−3 typed composites with novel arrangements of the electrodes and piezo-fibers, i.e., active fiber composite and macro fiber composite, are gaining increasing interests due to their excellent sensing and actuation properties.

2.3 Active fiber composites

Active fiber composite (AFC) was developed by the Active Materials and Structures Laboratory at MIT [19], as shown in Fig. 3 [20,21]. It consists of a monolayer of

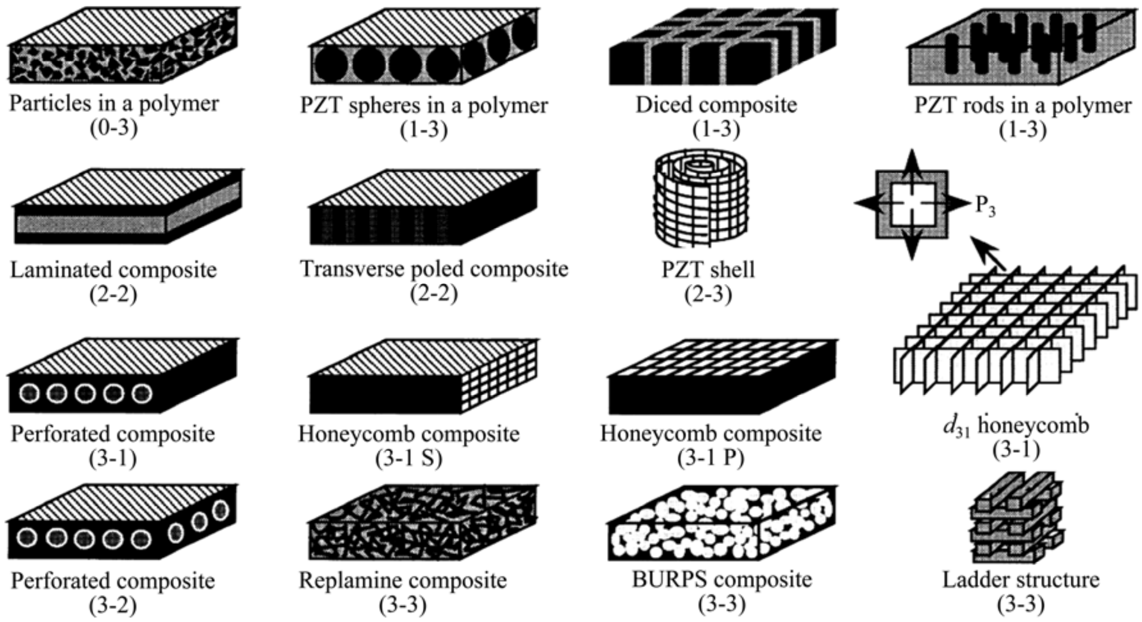

Fig. 2 Connectivity of constituent phases in piezoelectric ceramic–polymer composites [16]

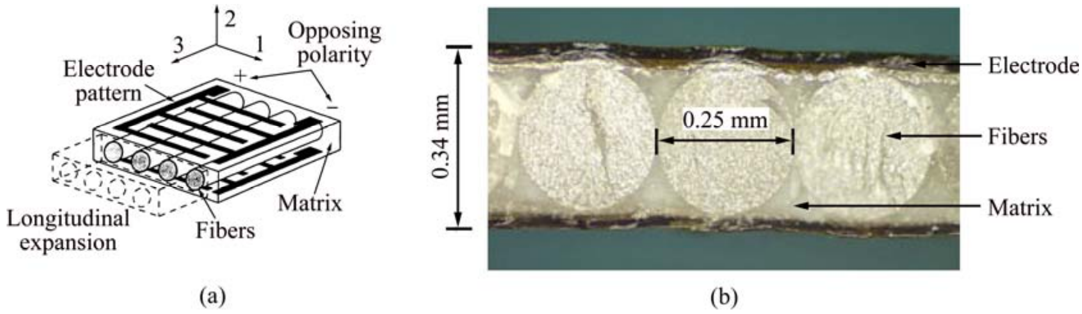

Fig. 3 Schematic structure (a) [20] and cross section (b) of active fiber composite [21]

continuous, aligned, unidirectional piezoceramic fibers embedded in polymer matrix to provide in-plane actuation. Piezoceramic fibers still keep much of the actuation capability of the bulk ceramic, and have higher strength than the monolithic form due to the decreased volume fraction of flaws [22]. Piezoceramic fibers embedded in polymer matrix could be thinner, thus less stiff in bending than a monolithic wafer.

Despite higher strength, piezoceramic fibers tend to crack at relatively low mechanical strains due to their brittle nature [23]. The polymer matrix could provide an efficient path for load sharing among fibers, transfer the stress around broken fiber when the damage occurs and prevent a crack in a fiber from propagating to adjacent fibers. All of these could allow AFC to withstand higher mechanical strains than individual fibers, and prevent macroscopic damage at high mechanical strains. AFC therefore exhibits improved reliability and structural properties, especially in views of the macroscopic and catastrophic damages resulting from cracks at very low strains in conventional piezoceramic wafers. Furthermore, the polymer matrix provides AFC the flexible nature which allows it to be more easily incorporated into or bonded to the curved structures.

Piezoceramic fibers embedded in the matrix are sandwiched between two layers of polyimide film that has a conductive electrode pattern printed in the inner surface. The utilisation of interdigitated electrode (IDE) enables taking advantage of d_{33} piezoelectric effect along the length of the piezoceramic fiber versus the conventional d_{31} piezoelectric effect used in most monolithic piezoelectric wafers [19]. This allows for anisotropic actuation and leads to the actuation performance of AFC superior to existing commercial piezoelectric actuators. These distinctive structural features and piezoelectric properties make AFC an interesting component for smart applications in various fields, such as vibration control, morphing, structural health monitoring and so on.

However, there also exist many factors which can easily influence AFC's performance. The difficulty of handling piezoceramic fibers during assembly process is one major disadvantage of AFC technology. Circular shaped piezo-fibers with diameters of 100−250 μm are commonly employed for the fabrication of AFC. The alignment of the fine fibers to form the piezoelectric monolayer is typically carried out manually, which often results in broken and poorly aligned fibers. Manual assembly process with high precision in fiber alignments unavoidably leads to complex procedures and increased manufacturing costs. Furthermore, air bubbles are difficult to be removed out completely when applying the polymer to fibers, even after the vacuum process, which greatly increases the chance of electrical failure [24]. Besides, AFC structure itself has disadvantages influencing the performance. Firstly, high operating voltages are required to produce the driving electrical field, which is primarily determined by the spacing between the IDE fingers, make AFC impractical in many realistic applications. Secondly, the small contact area between the circular cross-sectional fiber and IDE finger is an additional major disadvantage, which leads to the existence of low permittivity matrix. The matrix between the electrode finger and fiber not only makes driving voltage higher, but also accumulates most of driving electric field and leads to weakened and inefficient transfer of the electric field into piezo-fibers [25]. These result in reduced working efficiency of the AFC.

2.4 Macro fiber composites

Macro fiber composite (MFC) was developed at NASA Langley Research Center [26]. The primary constituents of MFC are the same as that of AFC, namely, piezoceramic fibers, IDE and polymer matrix. So MFC retains the most advantageous features of AFC, e.g., high strain energy density, directional actuation, conformability and durability. However, rectangular cross-sectional, unidirectional piezoceramic fibers instead of circular cross-sectional fibers are employed in MFC to be embedded in a thermosetting polymer matrix. The principal components of MFC and their structural arrangement are shown in Fig. 4.

The piezo-fiber sheets in MFC were fabricated by machining piezoceramic wafers using a dicing method [22]. Comparing to individual fibers, the sheets could be easily handled, allowing the piezoceramic fibers to be precisely aligned during assembly process. Producing and handling piezoceramic fibers in precise groups reduces the production cost of MFC device. This fabrication technique is also precise, repeatable and easily automated. The flat surfaces of rectangular fibers permit the maximum and direct contact with electrode fingers, thus ensuring the most efficient transfer of electric field into the fibers. In addition, the fiber volume fraction of MFC could reach up to 0.824 [27], while the maximum fiber volume fraction of AFC is less than 0.785 because of the restriction in the fiber geometry. Larger fiber volume fraction enhances the performance and improves the stiffness and strength of MFC. As a result, the actuation performance of MFC is almost 1.5 times that of AFC. And the experimental results showed that, after more than 90 million electrical cycles, the actuation performance of MFC is also superior to many other commercially available piezoceramic actuators, both with and without IDE [26].

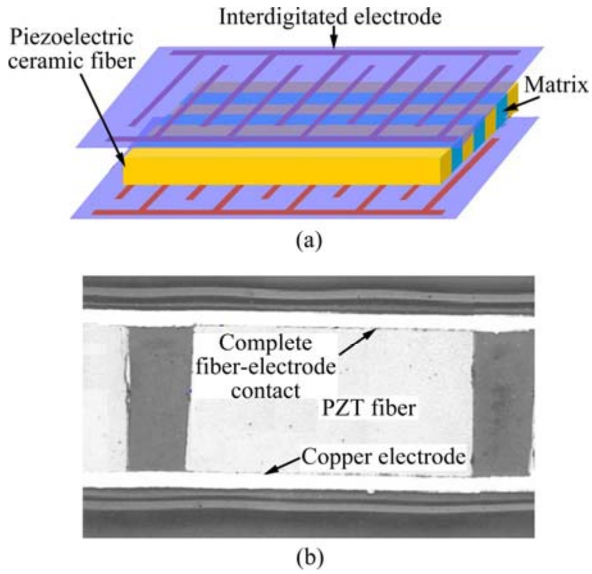

Fig. 4 Schematic structure (a) and typical cross section (b) of macro fiber composite [26]

3 Modeling of performance of AFC/MFC

3.1 Linear characterization of AFC/MFC

Figure 5 illustrates the electric field distribution along the piezoceramic fiber in the AFC/MFC with IDE electrode structures, which was obtained by finite element modeling, where the lines represent the strength and direction of the electric field [28]. Between two adjacent electrode fingers, the electric field lines are homogeneous along fibers and perpendicular to the plane of the IDE beneath the electrodes. Furthermore, the electric field lines concentrate near the electrodes and become dispersed and even in other areas, resulting in an inhomogeneous electric field distribution. The electric field distribution influences the performance of AFC/ MFC, which is controlled by the geometric parameters

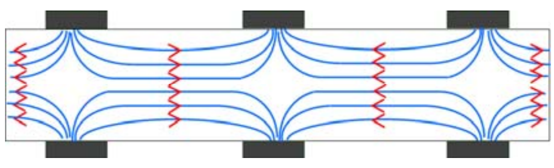

Fig. 5 Vertical section of AFC/MFC with IDE, qualitatively illustrating distribution of electric field lines

of the electrode design, e.g., electrode finger width, electrode finger spacing and the fiber thickness.

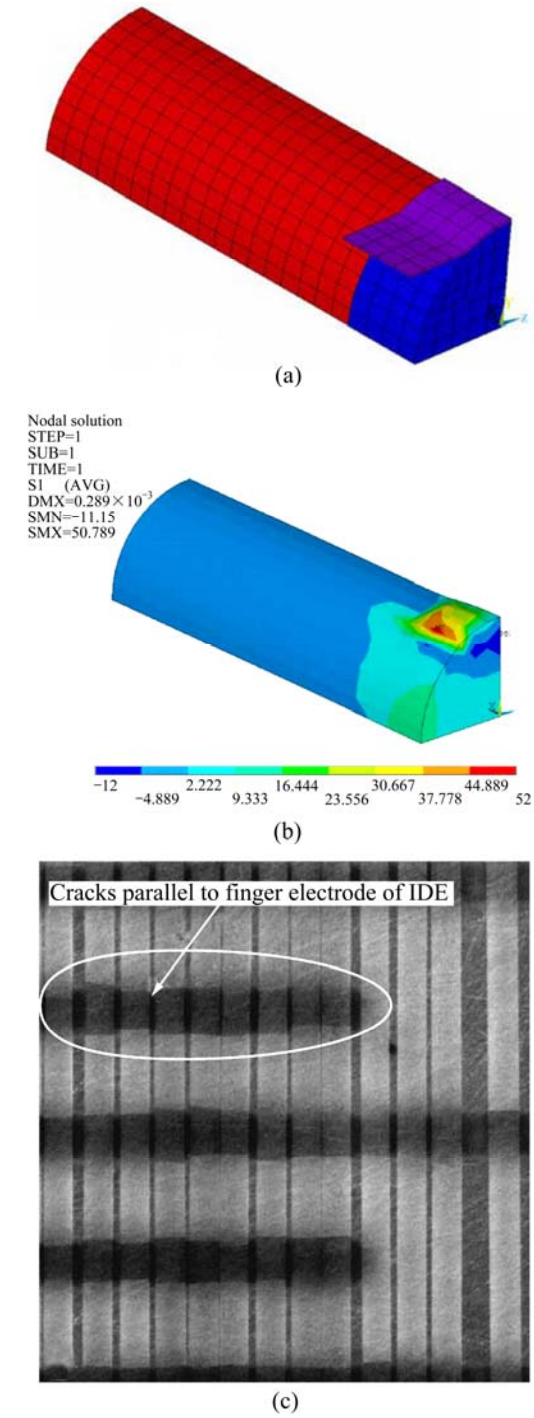

Fig. 6 RVE of AFC (a), first principal stress distribution in RVE (b) and section of fragmented AFC with cracking locations (c) [33]

Both analytical and numerical methods had been used to predict the performances of AFC/MFC and investigate the influence of configuration parameters on the actuation behavior of AFC/MFC. According to ROSSETTI et al [29] and WARKENTIN's [30] reports, smaller ratio between the electrode finger spacing and fiber diameter could lead to good actuation at lower voltages, which however was less efficient due to the steep curvature of the electric field in the vicinity of the electrode areas. On the contrary, larger ratio between the electrode finger spacing and fiber diameter resulted in more efficient actuation, but required higher driving voltage to achieve actuation at the same field level.

BECKERT and KREHER [31] investigated the influence of various geometrical and material parameters on the deformation performance and on failure hazards due to field concentrations. The results showed that both decreasing the electrode finger width and increasing the electrode finger spacing could improve the actuation performance. Additionally, the electric field distribution between the electrode fingers was investigated for various electrode widths, while the deformation was predicted considering the interlayer between the electrode and fibers with various thickness and permittivity. The results gave valuable insight into correctly approximating the average electric field in the piezoelectric composites for a given applied voltage.

BOWEN et al [28] investigated the nonuniform electric field distribution and strain distribution developed between electrode fingers on a monolithic piezoceramic substrate using finite elements. The results showed that 80% of the theoretical maximum strain could be achieved with electrode spacing to substrate thickness ratio greater than 4. The optimum strain was found to occur when the electrode width equals half of the substrate thickness, and a reduction in the substrate thickness could increase the strain output.

An optimum design should provide a compromise combining a high effective deformation with a sustainable failure hazard due to local field concentrations during operation. PARADIES et al [32,33] investigated the stress distribution in the unit cell of AFC, namely representative volume element (RVE) which is shown in Fig. 6(a). Instead of assuming the piezo-fiber with homogeneous polarization and properties, different properties due to different polarization states were considered. The first principal stress distribution obtained with a specially coded finite element routine is shown in Fig. 6(b), and higher stresses are distributed in the right side of this RVE unit. The numerical results indicated stress concentrations at the tip of the finger electrode. A fragmented AFC specimen is shown in Fig. 6(c), and the dark horizontal region was the shadow of the bottom IDE finger. The experimental result showed the cracks existed parallel to the IDE fingers, corresponding to the modeling result. The modeling approach allowed for a better understanding of the overall effects in piezoelectric materials with IDE structures.

MARTINEZ and ARTEMEV [34] studied the effect of broken fibers on the performance of AFC. The cracks in the fiber resulted in the loss or a significant reduction in the electric potential, while the electric field concentrated around the cracks. All of these led to the loss of the actuation and sensing performance, which could be up to 10% with only three broken fibers compared to the composite with undamaged fibers.

3.2 Nonlinear characterization of AFC/MFC

Since the AFC/MFC is capable of inducing high free-strains up to ~2000 με and is often incorporated into structures that operate under large strains [35], nonlinear behavior becomes significant. As discussed above, the linear behavior of the AFC/MFC is well described, however, actuation under high fields leads to more complex nonlinear material behavior.

WILLIAMS et al [27] derived nonlinear models for coefficients of thermoelastic properties of MFC as a function of temperature based on finite element and classical lamination analysis. The temperature-dependent properties of each constituent material, i.e., Kapton, acrylic, copper, epoxy and PZT, were obtained, and the orthotropic layer properties were calculated using a variety of micromechanics models. The classical lamination analysis was used to derive equations for the four independent stiffness parameters and two coefficients of thermal expansion of MFC. The results of classical lamination analysis were compared to that of the finite element, both of which agreed closely with each other.

WILLIAMS et al [36] measured four independent linear elastic engineering constants E_1, E_2, v_{12} and G_{12} of the orthotropic MFC in the linear elastic region, and characterized the nonlinear constitutive behavior under short-circuit conditions using standard tensile testing procedures. Various nonlinear plastic deformation models, e.g., elastic-linear hardening, Ramberg-Osgood, quadratic least-squares methods were used to fit the experimental results. And the experimental results were used to characterize the nonlinear tensile and shear stress-strain behavior and Poisson effects. The results gave valuable view of the short-circuit mechanical behavior of the MFC, including both values for essential elastic engineering constants as well as equations designed to handle even complex plastic deformation.

WILLIAMS et al [37] thoroughly investigated the nonlinear actuation behavior of MFC with monotonically increasing electric fields under a variety of mechanical load/stress levels. A nonlinear constitutive model was developed from the Gibbs thermodynamic potential function for a piezoelectric continuum and the piezoelectric coefficient of MFC under mechanical and electrical loadings was measured. The results showed that the absolute values of d_{31} and d_{33} increased and the strain-field behaviors of the MFC became more linear under higher DC offset voltages. Furthermore, the induced DC offset strains were nearly a linear function of DC bias voltage.

Besides high electric field discussed above, the polarization reversal is another factor being induced to nonlinear behavior. PADHEEA and HARURSAMPATH [38] developed an asymptotically correct micro-mechanics model with all possible electro-mechanical coupling effects using variational asymptotic method for predicting nonlinear behavior of MFC. SHINDO et al [39] examined theoretically and experimentally the nonlinear electromechanical response of MFC. Finite element analysis was used to study the strain and internal electromechanical fields near IDE fingers by introducing a model for polarization switching, which considered partially or fully poled states of piezo-fibers due to the inhomogeneous electric field distribution. The results of the strain versus electric field curves obtained from microelectromechanical models and simple experiments were compared with those from the finite element solution.

4 Applications of AFC/MFC

The development of smart structure technology offers great potential in the field of actuation and sensing. The superior performances, e.g., the ability to conform to the curved surfaces, the capability of large area coverage and anisotropic actuation and sensing, permit AFC and MFC to be easily bonded to or integrated into host structures. These benefits broaden the applications of piezocomposites compared with the conventional piezoceramic system.

4.1 Vibration control

The piezoelectric damping system for controlling the structural vibration has been developed in various engineering fields, e.g., aeronautical, space, civil, acoustic, semiconductor production, information, sports engineering and so on. The capability of piezoelectric material allows engineers to design not only active damping system but also passive damping system. MFC had proven to be useful in a variety of vibration control and noise control of structures [40−42]. In the past decades, applications on rotary-wing and fixed-wing aeronautical system, ultra-lightweight spacecraft structures and active twist control of rotor blades have always been a hot topic in academia and industry. CHEN et al [43] employed a hydraulic rudder actuator to control the first bending mode of a full-scale F/A-18 vertical fin, and distributed MFC actuators bonded on both sides of the vertical fin surface to control first torsional mode, as shown in Fig. 7(a). To reduce the premature fatigue failure of the structure and increase the mission availability, a novel hybrid actuation system was developed to actively alleviate the buffet response, as shown in Fig. 7(b). The results showed that the structural responses were suppressed under representative buffet load spectra, and dynamic strain and acceleration at the aft fin root were reduced to 41% and 43%, respectively. In addition, compared to the hydraulic rudder actuator, the high frequency response capability of MFC actuators provided more consistent performance under increased buffeting load levels [43].

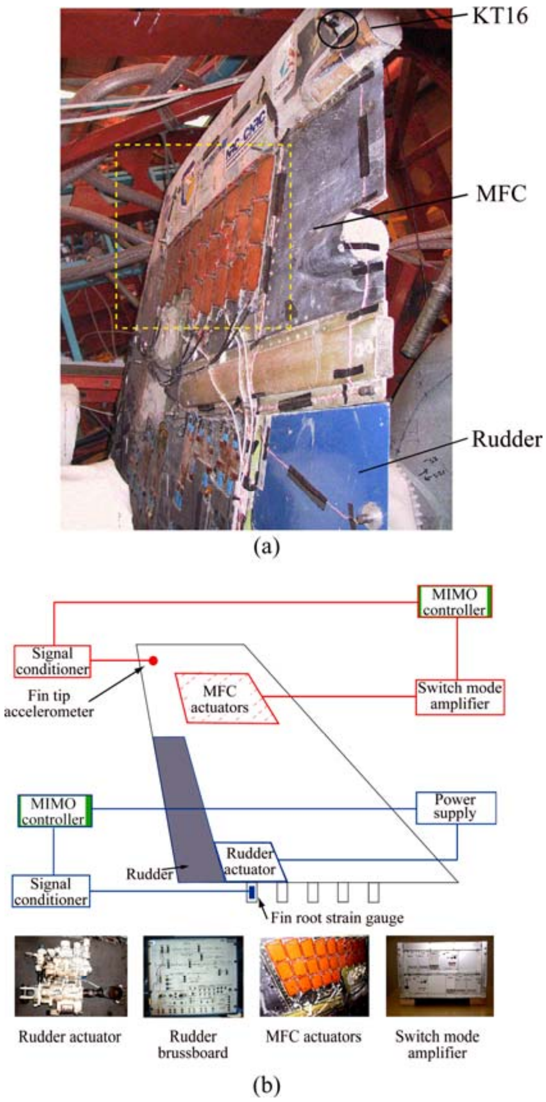

Fig. 7 Buffet load alleviation system on F/A-18 (a) and configuration of hybrid actuation system (b) [43]

MFC actuators have been investigated for mode testing of Gossamer Space Structures, such as, solar sails in a vacuum environment, and rigidizable inflatable antennas. Figure 8(a) and (b) show an integrated actuator-boom test component prior to and after inflation and rigidization, respectively. The boom consisted of three graphite fiber unidirectional plies [0/90/0] in a proprietary thermosetting epoxy resin system, and four MFC actuators were embedded within the composite structure of the boom near the base [44]. The embedded MFC actuators were capable of surviving the composite integration, folding and packaging, vacuum deployment and thermal rigidization processes in vacuum and subsequently operating at their full capacity. TARAZAGA et al [44] demonstrated successful vibration suppression of a space rigidizable inflatable composite boom containing embedded MFC actuators. Velocity-proportional and acceleration-proportional controllers were utilized and capable of attenuating fundamental bending response significantly using only modest control authority, achieving –23 dB with 10% of available voltage.

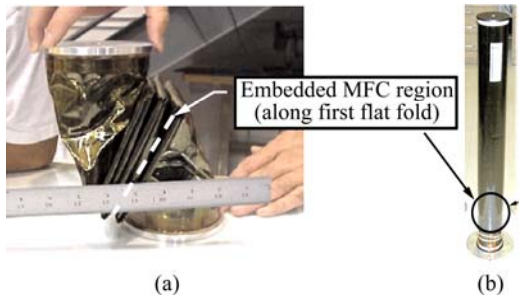

Fig. 8 Rigidizable inflatable composite with integrated MFC before curing (a) and after curing (b) [44]

4.2 Energy harvesting

Energy harvesting could be used to capture energy from the ambient environment, e.g. solar loads, wind loads, thermal gradients or mechanical vibration, and convert them into electrical energy to provide energy supply to electronic devices. Compared to the traditional piezoelectric materials, MFC is characterized by its flexibility with large deformation. SODANO et al [45,46] compared the efficiency of the three energy harvesting devices using monolithic PZT, Quick Pack, and MFC, and identified the feasibility of their use in practical applications. To further improve the efficiency of MFC, the geometric configuration of an energy harvesting system [47,48] and optimized energy harvesting circuit [49] were investigated. Figure 9 shows the experimental setup of the energy harvesting device with two MFC patches bonded to a cantilever beam in a sandwich structure. An electromagnetic shaker for generating sinusoidal vibration, an accelerometer for measuring the input acceleration excitation level, a strain gage for tuning the natural frequency, a full-bridge rectifier, a capacitor and an electrical load for obtaining voltage were also used in this energy harvesting system. A peak value of the generated power could be up to 45.6 V [48].

4.3 Structural health monitoring

Structural health monitoring is an emerging field that holds great potential to enable condition-based maintenance and safely prolong the useful life of aerospace and mechanical structures. So far, the use of AFC and MFC had been explored in selected nondestructive tests for defect detection in various structures, e.g. railroad and cylindrical pipeline [50−52]. TARAZAGA et al [53] utilized MFC as sensor/actuators to detect the damage of a space inflatable rigidizeable boom structural. The results showed that MFC with the impedance method was sufficiently sensitive to detecting very small amounts of damage, and more effective in detecting far-field damage than near-field damage.

4.4 Morphing

There is rapidly growing interest in morphing structures, which are able to change shape or state, in response to the environment or in order to change operating characteristics. This is particularly important in aerospace industry, while morphing aircraft could be achieved by the change of airplane wing geometry, replacement of mechanically driven control surfaces, control of helicopter blade and reliable actuators [54]. KIM and HAN [55] designed and fabricated a smart flapping wing by using a graphite/epoxy composite material and an MFC actuator, aiming to mimic the flapping motion of birds. The results of wind tunnel tests showed that the deformation of the wing surface generated by the MFC was enough to control the lift and thrust, and a 20% increase in lift was achieved by changing the camber of the wing at different stages of flapping motion. PARADIES and CIRESA [56] designed and manufactured an active composite wing with a wing span of 500 mm with seven integrated MFC elements including six MFCs on the upper surface of the wing and one MFC on the lower surface close to the wing root, as shown in Fig.10. A total 4.3 mm displacement was obtained at the tip of the wing by the integrated MFC elements working at 1.5 kV, and in total a roll moment of 0.17 N·m was generated in the demonstrator active wing. Although the roll moment of the active wing was small

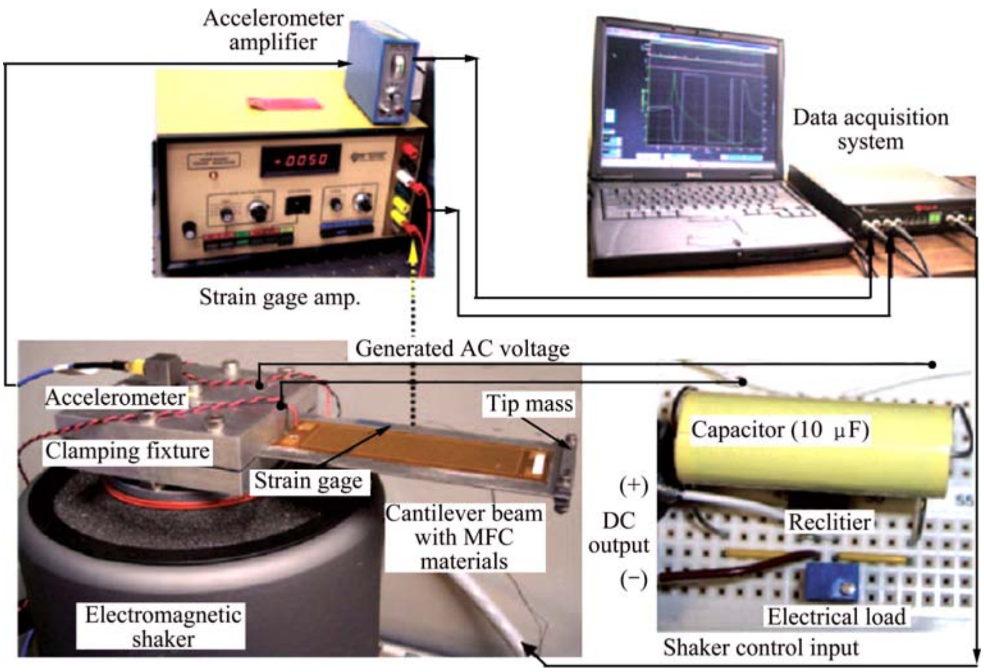

Fig. 9 Photograph of experimental setup of energy harvesting device with MFC [48]

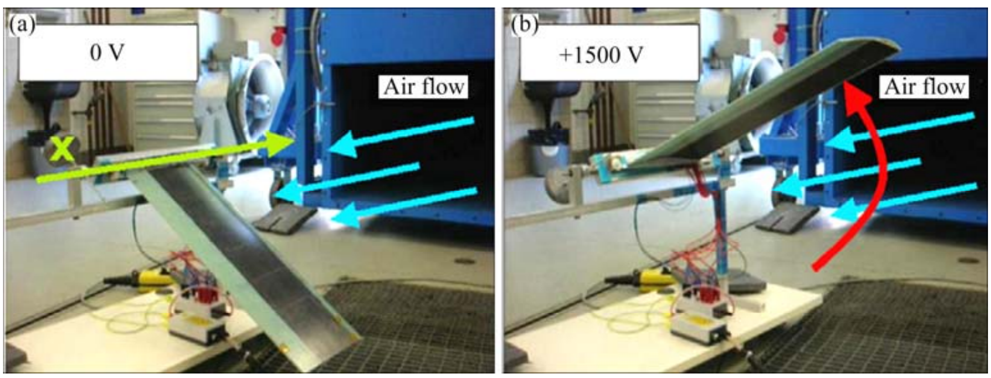

Fig. 10 Active wings with deactivated and activated MFC in air flow [56]

in comparison with that of a conventional aileron, it was sufficient for the roll control of unmanned aerial vehicle.

5 Conclusions

Active fiber composite and macro fiber composite composed of piezoceramic fiber, polymer matrix and interdigitated electrodes offer many advantages over the traditional monolithic piezoelectric devices such as conformability and robustness, high actuation energy densities, anisotropic actuation, and tailorable mechanical properties. The linear and nonlinear behavior predictions by evaluation of structure parameters and properties of consistent materials were summarized. Additionally, several industrial applications employing these active materials were presented and discussed. While much work involving these devices is currently at the research and development level, piezoelectric fiber composites hold a great deal of potential for commercial and industrial applications.

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压电纤维复合材料的发展、模拟及应用

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摘　要：压电材料同时具有驱动和传感性能，被广泛应用于各种智能结构中。圆形压电纤维复合材料和方形压电纤维复合材料作为两种新型压电复合材料，因其独特的结构而具有比压电陶瓷片更优异的性能。采用数值法和分析法对复合材料的结构参数及各组分材料性能进行评估从而预测复合材料的性能是目前的研究热点。压电纤维复合材料被广泛应用于振动及噪声控制、结构健康监测、结构变形及能量收集等领域，并能对上述领域的进一步发展发挥关键作用。

关键词：压电；圆形压电纤维复合材料；方形压电纤维复合材料；模拟；智能应用

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