Piezoelectric Actuators
Metal Core Piezoelectric Complex Fiber and Application for Smart System

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ABSTRACT
We produced a new metal-core piezoelectric fiber by means of both hydrothermal and extrusion methods. The insertion of a metal core was significant in view of its strength—greater than that of ceramic materials—and in that electrodes are not required in the fiber’s sensor and actuator applications. A new smart board was designed by mounting these piezoelectric fibers on the surface of a CFRP composite, and the sensor and the actuator function were evaluated. We showed that self-sensing was possible using this smart board. And function as a sensor and actuator, this board can control the vibration.

Introduction
Piezoelectric material can be used in sensing and actuating applications. Much attention has recently been paid to the application of piezoelectric materials in smart structures such as health monitoring devices and for vibration control by embedding them into composite materials such as Carbon-fiber Reinforced Plastic (CFRP) and Grass-fiber Reinforced Plastic (GFRP). In embedding piezoelectric materials into composite material, it is essential to minimize the inclusion effect on the mechanical performance of the composite. As one solution, the Active Materials and Structures Laboratory at MIT has proposed the use of fiber-shaped piezoelectric material (APC) [1][2]. In their research, thin PZT fibers are transversely aligned in a polymer matrix and the fiber laminates are put between interdigital electrodes (IDT) at a right angle in order to obtain a larger d33 mode strain along the fiber axis. However, their fiber has disadvantages, as only IDT can be used as sensors and actuators in this application and the fragility of ceramics may be problematic. In order to solve these problems, we propose the use of a piezoelectric fiber having a metal core, which is fabricated by means of the hydrothermal method. Our piezoelectric fiber has the following advantages: (1) No need of electrodes. (2) High Performance. (3) Durability (4) High resistance to external noise (5) Low cost[3].

In this paper, we describe the fabrication of piezoelectric fibers with metal cores using two techniques — the hydrothermal method and the extrusion method, as well as the design of a CFRP smart board using these piezoelectric fibers[4]. In addition, we show that this smart board has the capability to act as both a sensor and an actuator. Using a sensor and actuator function, this board can be able to know own state, and to suppress own vibration.

Metal Core-Piezoelectric Fiber
Embedding a sensor and an actuator in the composite structure enables health-monitoring and vibration-suppression functions to be performed. However, it is necessary to consider the shapes of the sensor and the actuator to minimize their possible harmful influence on the mechanical performance of the composite material. This influence can be reduced by embedding the piezoelectric fiber along the same direction as that of the carbon fibers in the CFRP composite. A CFRP prepreg sheet is usually 0.12mm thick (Toray T700S). The diameter of the buried fiber should thus be 0.24mm or less when two sheets of CFRP prepreg are used. The piezoelectric film
should also be thick enough to provide insulation between the film’s metallic wire and the CFRP composite materials. Thus, we assumed the diameter of a piezoelectric fiber to be 0.2mm.

**HYDROTHERMAL METHOD**

Piezoelectric fibers with metal cores were fabricated using the same hydrothermal method reported by Shimomura at the Tokyo Institute of Technology [5]. Higuchi et al. have recently improved the film-formation condition [6].

In the hydrothermal process, PZT is precipitated according to the following reaction.

\[
\text{Pb}^{2+} + (1-x)\text{Zr}^{4+} + x\text{Ti}^{4+} + 6\text{OH}^- \rightarrow \text{Pb}((\text{Zr}_{1-x}\text{Ti}_x)\text{O}_3 + 3\text{H}_2\text{O}
\]

This method consists of two processes: nucleation and crystal growth. In the nucleation process, a titanium wire was hydrothermally treated in a mixed solution of zirconium oxychloride, lead nitrate, and potassium hydroxide in an autoclave. The reaction condition was at 140°C for about 24h. The solution provided the Pb²⁺ and Zr⁴⁺ ions, and the titanium substrate itself was the source of the Ti⁴⁺. Ultimately, PZT nuclei formed on the titanium substrate surface.

After nucleation, the titanium substrate was subjected to the crystal growth process in order to increase the thickness of the PZT layer. Titanium tetrachloride was added to the above solution as a further Ti⁴⁺ source, and a hydrothermal reaction progressed at 120°C for about 24h. Subsequently, PZT crystals were grown on the nuclei. Figure 1 presents an SEM image of the crosssection of piezoelectric fiber. Figure 1(a) shows that the 150μm diameter titanium wire is uniformly covered by PZT film about 20μm thick.

**EXTRUSION METHOD**

Although the hydrothermal method can uniformly form a piezoelectric layer about 20μm thick on the titanium wire surface, the PZT clad is not thick enough for actuator use. Therefore, an extrusion technique was attempted in order to produce a slightly thicker PZT clad.

In this process, PZT powder was mixed with binder and water, and the resultant paste was extruded from a nozzle through a platinum fine line. After drying at room temperature, defatting and sintering were performed continuously in a movable furnace (1150°C), which moved from one end of the fiber to the other. The piezoelectric film was then polarized by applying 300V DC between the metal core and the CFRP matrix at room temperature. Figure 1(b) presents an SEM image of the cross section of the PZT fiber after the sintering process. This photo depicts the platinum wire in the center; the diameter of the piezoelectric fiber is about 200μm.

(a) Cross section of piezoelectric fiber fabricated by hydrothermal method
(b) Cross section of piezoelectric fiber fabricated by extrusion method

Fig. 1 SEM image of a Metal Core Piezoelectric fiber
Application to the Smart Board

Piezoelectric fibers were placed on a six-layer stack of CFRP prepregs \([0_2 / 90_2 / 0_2]\), as illustrated in Fig. 2. We used Toray T700S as general, one-direction CFRP composite materials (Toray T700S; elastic modulus 235 GPa, strength 5 GPa, elongation 2.1\%). The stack was pressed under 0.3MPa at 135°C for two hours using a hot press. A cantilever structure made of the CFRP composite was then produced in order to evaluate the sensor and actuator functions.

Figure 3 presents a cross-section of the smart board. Our piezoelectric fibers are embedded in the 0° layers. The CFRP composite can be used for electrodes because the circumference of the piezoelectric fiber is covered with carbon fibers.

Use as actuator and sensor

The piezoelectric material needs two electrodes (an upper electrode and a lower electrode) when used as a sensor and an actuator. However, in our smart composite board, an electrode is not required. The metal core in the fiber can be used as one electrode, and CFRP composite matrix can act as a ground electrode because of the high electric conductivity of the carbon fiber. By applying voltage between the metal cores and the CFRP matrix, the piezoelectric fibers were elongated or shrunk due to the inverse piezoelectric effect. The elongation deformation is generated when the voltage is applied to the fiber. Eventually, the CFRP board was deformed by the deformation of the piezoelectric fibers.

By applying mechanical stress, electric polarization can be produced in the piezoelectric materials. As the piezoelectric fiber on the CFRP board was shrunk or elongated corresponding to the movement of the board, an electric charge should be generated from the piezoelectric fiber owing to the piezoelectric effect.
**Sensor and actuator function**

In this experiment, 31 piezoelectric fibers were mounted in the cantilever structure. This cantilever is 180mm in length, 30mm in width, and 0.7mm in thickness. Thirty fibers were used for the actuator, and 1 fiber was used for the sensor. By applying 20V AC voltage between the 30 platinum cores and the CFRP composite body, the CFRP board was vibrated by the deformation of the piezoelectric fibers. The vibration of the cantilever tip was measured using a laser displacement meter and output voltage from one sensing piezoelectric fiber. Figure 4 shows the relationship between the frequency of the applied voltage, the vibration displacement of the beam end, and the output voltage from the sensing piezoelectric fiber. The solid line indicates the displacement of the beam tip measured by a laser displacement meter, and the dotted line expresses the output voltage from the piezoelectric fiber. It can be seen from the figure that the cantilever end vibrates at an amplitude in the range of about 1 μm to 14 μm showing a resonant frequency at about 45Hz. As well, the output voltage from the fiber is almost proportional to the magnitude of the reference vibration. The phase of the output voltage has changed at the resonance frequency by 180 degrees. In other words, it is understood that the driving voltage doesn’t leak to the output voltage, but that the signal can be read in terms of the bending of the board.

Next, we discuss the active vibration control of smart board. We performed the control experiments of the CFRP composite beam by using piezoelectric fibers as a sensor and actuators. In this study, 3 fibers are used as a sensor to detect a vibration, and the others are utilized as actuator to suppress a vibration. Figure 5 demonstrates the displacement of the beam tip. The disturbance is generated before starting the control by inducing a vibration through the application of 20V for the second at a first mode frequency. The solid line indicates the response with control, and the broken line indicates response without control.

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![Fig. 4 Relationship between applied frequency, vibration displacement of the beam end, and output voltage](image)

![Fig. 5 Vibration suppression of the smart board by active vibration control](image)
CONCLUSION

These newly developed piezoelectric fibers are expected to promote high-level applications in the construction of health-monitoring and vibration-control systems.

Piezoelectric fibers with metal core wire were successfully fabricated by both hydrothermal and extrusion methods, and a new smart board was designed by mounting these piezoelectric fibers on the surface of the CFRP composite. These complex fibers can function as sensors and actuators in the CFRP board. In the hydrothermal method, unlike the extrusion method, the PZT composition deviated from the ideal to a PZT-richer side, and it was very difficult to control the composition ratio. In addition, the film was as thin as 20um. In this technique, however, the diameter of the metal wire can be decreased to 100um or less. Since the thinner fiber is better for reducing the inclusion effect in the composite, the hydrothermal fiber should be suitable for sensor use. It is difficult to reduce the fiber diameter to 200um or less using the extrusion method; this fiber is adequate for use as an actuator because of its reasonable actuation power. Using a sensor and actuator function, this board can be able to know own state, and to suppress own vibration. Further advanced applications of these piezoelectric fibers can be expected in the construction of self-sensing, health-monitoring and vibration-control systems.

References

Pressure Loading of Piezo Composite Unimorphs

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ABSTRACT

Over the past decade synthetic jets have emerged as a promising means of active flow control. They have the ability to introduce small amounts of energy locally to achieve non-local changes in the flow field. These devices have the potential of saving millions of dollars by increasing the efficiency and simplifying fluid related systems. A synthetic jet actuator consists of a cavity with an oscillating diaphragm. As the diaphragm oscillates, jets are formed through an orifice in the cavity. This paper focuses on piezoelectric synthetic jets formed using two types of active diaphragms, Thunder® and Lipca. Thunder® is composed of three layers; two metal layers, with a PZT-5A layer in between, bonded with a polyimide adhesive. Lipca is a Light Weight Piezo Composite Actuator, formed of a number of carbon fiber prepreg layers and an active PZT-5A layer. As these diaphragms oscillate, pressure differences within the cavity as well as average maximum jet velocities are measured. These parameters are measured under load and no-load conditions by controlling pressure at the back of the actuator or the passive cavity. Results show that the average maximum jet velocities measured at the exit of the active cavity, follow a similar trend to the active pressures for both devices. Active pressure and jet velocity increase with passive pressure to a maximum, and then decrease. Active pressure and the jet velocity peaked at the same passive cavity pressure of 18kPa for both diaphragms indicating that the same level of pre-stresses is present in both actuators even though Lipca produces approximately 10% higher velocities than Thunder®.

INTRODUCTION

Methods that attempt to control the motion of fluids have been extensively explored in the past. Some of these methods can be passive or active or both [1]. Passive flow control is usually achieved using steady state tools such as wing flaps, spoilers, and vortex generators, among others. These techniques though effective have marginal power efficiency and are not capable of adjusting to the instantaneous flow conditions experienced during flight. Active flow control (AFC) methods however, are much more efficient as they can adapt to the constantly changing conditions by introducing small amounts of energy locally to achieve non-local changes in the flow field with large performance gains [2,3,4]. The simplification of conventional high lift systems by AFC could possibly lead to providing 0.3% airplane cost reduction, up to 2% weight reduction and about 3% cruise drag reduction [5]. In spite of all the advantages, using active flow control devices usually adds complexity in design, and increases manufacturing and operation cost of the system preventing their use. For this reason, many researchers have focused on designing better active flow control devices that are easy to manufacture, are small in size and require little power to operate. One of the devices that fulfill all of these qualities is called synthetic jets.

Synthetic jets consist of a cavity with an oscillating diaphragm. When the diaphragm oscillates air is pushed out an orifice forming a jet [6]. The interaction of the jets with an external
flow leads to the formation of closed re-circulating flow regimes near the surface. These flow regimes can act as a "virtual surface" and consequently add an apparent modification of the flow boundary [4].

The oscillating diaphragm used in the synthetic jet cavity is usually driven using electrical or mechanical power. In the past, researchers have used compressed air or regulated blowers as a means of supplying steady or oscillating flow [7,8]. This adds to the complexity and weight of the system. Piezoelectric disks oscillate in the same manner as a piston or a shaker when driven using an AC electric signal. Eliminating the shaker or a piston reduces the number of moving parts, eliminates tribology issues and reduces weight. Hence, several investigators have adopted piezoelectric disks as oscillating diaphragms in synthetic jets [6,9]. The most commonly used diaphragm consists of a Lead Zirconate Titanate (PZT) disk bonded to a metal shim using a conductive epoxy, a Unimorph. Although these disks have been successful in generating high velocities, the devices operate at high off resonant frequencies, consequently requiring high amounts of power. In addition, driving the actuator at resonant frequencies causes debonding and heating of the individual layers shifting the resonance and causing the output of the device to drop and fail [9].

In the current study, piezoelectric composites that are more durable are used as active diaphragms in the jet cavity. In addition to active piezoelectric layers, they have reinforcing layers of metal or other stronger materials that give them added durability. These lightweight devices have the ability to produce micro scale displacements at fast response times. Such advantages make them suitable for flow control purposes as demonstrated by Mossi et al. [10,11]. In practical applications synthetic jets will be subjected to various pressure differentials within the cavity and also outside the cavity. In this study, the pressure differentials within the cavity are studied as the understanding of these internal pressures plays a crucial role in cavity design and jet performance.

EXPERIMENTAL SETUP

The two diaphragms used in this study are PZT based piezoelectric composites, Thunder® and Lipca. Both diaphragms are mechanically pre-stressed, due to a coefficient of thermal expansion mismatch between their layers. Thunder®, developed at NASA Langley Research Center, is composed of three layers; a 0.254 mm thick PZT-5A layer is sandwiched between a 0.0254 mm thick layer of chemically etched copper, type ASTM B152 Alloy 110, and a 0.254 mm thick layer of stainless steel, Type 304, bonded with a polyimide adhesive, LaRC-SI [12]. The PZT and copper layers have an overall diameter of 63.5 mm, and the steel layer has a slightly larger diameter, 68.5 mm, to allow clamping of the device, Figure 1a. The Lipca actuator, developed by Konkuk University, Korea [13], is composed of a top layer of glass/epoxy with a diameter of 63.5 mm, and the steel layer has a slightly larger diameter, 68.5 mm, to allow clamping of the device, Figure 1a. The Lipca actuator, developed by Konkuk University, Korea [13], is composed of a top layer of glass/epoxy with a diameter of 63.5 mm, and the steel layer has a slightly larger diameter, 68.5 mm, to allow clamping of the device, Figure 1a.

The synthetic jet cavity is constructed of two 88.0 x 88.0 x 19.1 mm Plexiglas™ pieces. The plastic pieces have a 60.5 mm circular aperture in the center. The actuators are placed in between the two pieces reinforced with a neoprene rubber ring, on both sides, to provide a cushion and a seal at the same time. Screws are used to seal the plastic pieces along with a 1.6 mm thick covering plate which provides a 3.67 mm axisymmetric orifice in the center.