Piezoelectric Tubes for Vibration Sensing and Damping

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CeraNova Corporation has developed a ceramic piezoelectric actuator/sensor array embedded in a composite. The array will enable the intelligent actuation and control of the smart composite at discrete locations to achieve greatly reduced vibration modes and increased aerodynamic efficiency leading to reduced fatigue in critical structural components. The array is composed of miniature ceramic piezoelectric tubes produced by powder processing. Vibration control was successfully demonstrated by 35 db vibration damping of a cantilever beam.

The near-term and long-term mission objectives of the aeronautic industry require new sensor and actuator materials that can be rapidly fabricated at reasonable cost into high performance parts. CeraNova demonstrated that a new class of ceramic piezoelectric sensors and actuators can be included in light-weight composites, and operate at wide frequency ranges and low voltages. A lead-zirconate-titanate (PZT-5A) was chosen as the piezoelectric material; a tube of approximately one millimeter diameter was the geometric objective; and a sensing and damping system bonded to an airfoil-cantilever beam was chosen as the demonstration vehicle. The success of our devices warrants further develop ceramic piezoelectric tubes for closed-loop vibration control in aeronautic structures applications such as wings, rotor blades, and tail sections. The success of this technology will benefit our near-term as well as long-term objectives, including vibration control, precision positioning devices, and sound control. The ceramics could be substituted for much more expensive, higher operating-voltage, and more massive structures that use ceramic piezoelectric plates and cut shapes.

The program goals were to demonstrate a practical process to produce unique ceramic piezoelectric microtubes for improved performance, and incorporate these tubes in a composite to demonstrate their sensing and damping abilities. We achieved these objectives by applying our innovative ceramic powder processing ability and our proprietary extrusion process experience to piezoelectric ceramics materials and technology. Two ceramic powder processing techniques, extrusion and film casting, were evaluated in this program. Extrusion was the preferred
processing technique since it provides a simple, high volume, low-cost and well-controlled way of producing high performance ceramic piezoelectric tubes.

Under this program, CeraNova Corporation evaluated a unique process to produce ceramic piezoelectric tubes and the application of the tubes for localized sensing and actuation to reduce vibrations in aerospace structures. The principal material concept examined was a lead-zirconate-titanate (PZT) type ceramic formed into miniature tubes. The tubes were electroded on the inside and outside surfaces, and poled through the wall thickness to create the piezoelectric devices. This design concept allows individual tubes to act as localized sensing and actuation devices that operate at very low voltages. The ceramic piezoelectric tubes bonded to an aluminum beam were able to dampen induced vibrations. The evidence suggests that an optimized design could result in a high degree of sensing and actuation of a wide range of vibration modes for many applications.

During the course of the program's effort, CeraNova Corporation successfully achieved the following major accomplishments:

- Specified a family of materials appropriate for many structural damping applications.
- Identified an epoxy-adhesive compatible with aluminum, the electrode metal and the ceramic piezoelectric.
- Performed piezoelectric and microstructural characterization tests on individual tubes.
- Constructed a test fixture to simulate an aircraft (see Figure 2.)
- Demonstrated ceramic piezoelectric tube ability to perform successfully as sensors and damping actuators under low frequency vibrations.

Processing and Testing

CeraNova Corporation has developed a proprietary process for producing fine filaments of ceramic materials using an extrusion process. Though extruding ceramics is a well known, wide-spread process in the industry, our process is unique in forming fine diameters of straight filamentary material at high speeds--applicable for cost-effective production. The flexible pre-fired filamentary material is pictured in Figure 1 along with sintered-electroded tubes. In an alternative process using a similar organic formulation, large sheets of the mixture were film-cast. Upon drying, the flexible cast was wrapped into a tube shape. This alternative processing technique was used to produce thinner and straighter tubes than could be extruded under the program's time constraints.

The prefired tubes were heat treated in a multi-step process. The prefired material was heated to remove the organic material. The bisque-fired pieces were then fired in a lead containing atmosphere to sinter the piezoelectric. A metal-containing paint was used to coat the
inside and outside surface of the tubes, and the samples were once again heat treated to firmly bond the metalization to the ceramic.

The tube samples were positioned in a machined cantilever beam, and wires were attached to the metalized surfaces by soldering. The beam was vibrated in a controlled manner, and while individual tubes were used to sense and record the vibration modes, others were used to dampen the motion.

The calculations for the resonance frequency of the 3 by 400 mm aluminum cantilever beam were as follows:

\[ f_1 = \frac{0.56T}{l^2} \left( \frac{E}{12\rho} \right)^{0.5} = 15.3 \text{ Hz} \]

\[ f_2 = 6.27 f_1 = 96 \text{ Hz} \]

At a measured frequency of 16 Hz, and a 10 V excitation on tube 5, 70 mV was recorded from tube 11. With a control voltage of 4.5 V 180° out of phase on tubes 3 and six resulted in a reduction of the tube 11 sensing to 1.5 mV, or about a 33 db damping. Similar tests using tubes 9 and 12 in place of 5, and a 25 V-180° control voltage on tube 11 resulted in a vibration damping of 35 db.
In an alternative test, the exciting and controlling tubes were not on the same column, and therefore, it was necessary to consider the additional phase difference between them. Tubes 9 and 12 were used as the exciting actuator sites, and tubes 3 and 6 as the controlling actuator sites. Tube 11 was used as a sensor. With an excitation voltage of 5 V at 16 Hz, 70 mV was sensed. Increasing the control voltage to 10 V (180° out of phase) reduced the sensing voltage to 30 mV. The additional phase difference that comes from the propagation of the acoustic wave can be seen. More tests are planned on this test fixture and with improved piezoelectric tubes.

CeraNova Corporation is a two-year-old independent high-technology ceramics manufacturing company located in Hopedale, Massachusetts. CeraNova performs government and commercial research and development and manufactures in three materials/products areas: filters, superconductor antennas, and ferroelectric devices.

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2 Morgan Matroc Company, Bedford, OH.