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THE INTEGRATED ELECTROMECHANICAL DEVICES FOR ACTIVE CONTROL OF VIBRATION AND SOUND

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Abstarct :
Advances in transducers and electronics have made possible integrated electromechanical devices for active vibration and noise control. This paper describes one such system which makes use of piezoelectric materials. An integrated device employing piezoceramic actuators and sensors, analog electronic signal conditioning, programmable control components, and a voltage amplifier is described. Issues driving design of each functional subsystem are addressed. The device is packaged using flex circuit technology and other electronics industry methods. The means of integrating transducers and other components are noted. Test results indicating the vibration suppression capability are presented, and the considerably greater possibilities for more sophisticated control designs using the same system are summarized. Potential applications in active vibration and sound control are described, and uses of the broader technology, beyond the specific device design, are summarized.

1. INTRODUCTION

The use of adaptive or smart materials in practical systems presents challenges which are often overlooked in basic research. Among the most important is the approach to integrating the materials with the other components necessary to produce a part, device or structure which performs required functions in a predictable and repeatable manner. This paper describes technology for combining one lass of smart material, piezoelectrics, with electronic components to create devices for active control of vibration and sound. There are numerous applications in precision systems where even a small level of vibrat ion or vibration-induced sound is unacceptable. In the past, these vibrations were often reduced by redesign or possibly by passive damping and isolation techniques. Active vibration control is an alternative solution that can yield increased performance with greater versatility. But active vibration control systems are usually heavier, bulkier, and more expensive. Piezoelectric transducers are one of the most common means of producing and measuring vibration and sound. The paper describes why piezoelectric actuators and sensors are especially well-suited to integration with passive and active electronic components to form active vibration control devices.

Piezoelectric transducers have enjoyed widespread use over the last decade for vibration control in university, corporate, and government research laboratories, but introduction into applications has been slow. As basic smart structures research continues, a near term possibility exists for discrete electroactive material-based vibration suppression components like the one shown in Figure 1 as add-ons to traditional structures

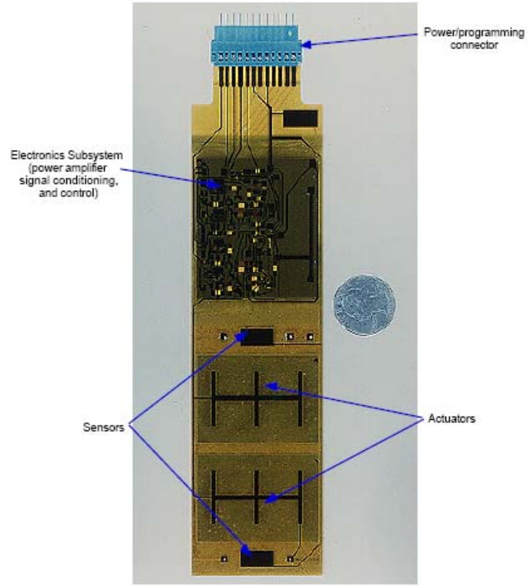

Figure 1: Top view of piezoelectric device

The paper begins by motivating the development of integrated active vibration suppression devices. It continues by outlining the roles of the various subsystems - actuation, sensing, signal processing (including control), and power conditioning - in the integrated system. The first two functions are performed by piezoelectric materials; the remaining trio is accomplished with an electronic subsystem. The paper concludes by summarizing the practical advantages of the technology as well as the open issues for improved integration, manufacturability, and performance. It describes how this technology can be incorporated into larger systems and suggests the types of economies of scale which would be realized with large scale production.

2. PASSIVE SUPPRESSION DEVICES AS FUNCTIONAL MODELS

Passive devices serve as functional models for their active counterparts, with the understanding that replication of passive functionality is only a starting point.

Figure 2 shows schematics of two common passive systems used for vibration suppression.

This device type can be attached to structures to add significant damping to a single mode or, in some cases, to additional modes close in frequency. It consists of a relatively thin layer of lossy viscoelastic material coated by a much stiffer constraining layer.

This distributed damping scheme is effective for vibration suppression over a somewhat broader frequency range.

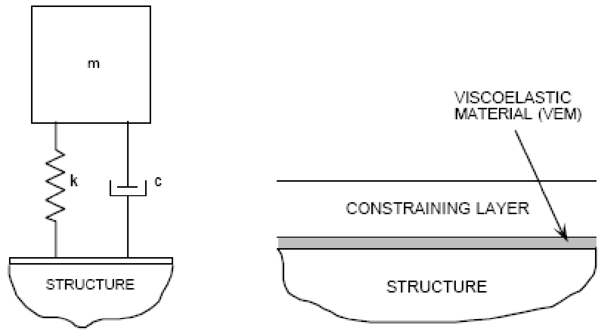

Figure 2: Modular passive damping systems with functionality desirable in an active piezoelectric device

Passive piezoelectric devices can be made to perform the same functions An active piezoelectric device capable of substituting for either or both of these passive systems while offering additional design freedom would be valuable for vibration suppression. With the proper control algorithm, either the single-mode damping of the TMD or the broadband damping of the viscoelastic treatment can be realized. The active damping performance has been achieved by numerous researchers using piezoelectric materials and laboratory supporting components and equipment, or occasionally using more compact supporting systems.

However, these combinations of components and devices are too costly, bulky, and impractical for most applications. Active vibration suppression devices will not enter widespread use if they function as nothing more than direct passive substitutes. Their additional cost must be justified by such features as programmability or adaptability. If it is done properly, integration of the components of an active system into a single unit can reduce cost while retaining additional functionality. Another benefit of an active system is the possible coordination of multiple devices to achieve a global objective.

3. INTEGRATED PIEZOELECTRIC DEVICES

The present development is at the same time a culmination of work begun more than a decade ago in development of “smart” or “intelligent” structures incorporating piezoelectric actuators, and a starting point for more advanced electromechanical integrated devices. The early smart structures work envisioned piezoelectric actuators and sensors combined with electronic components embedded in composite materials to create structures with artificial muscles, nerves, and brains.

The present device uses flex circuit and other technologies to achieve similar goals. In the previous work, electronic support systems, with a relatively high-capability digital signal processor included, were integrated in a standalone compact package called the Modular Control Patch The current devices incorporate less local processing power, and distribute it with the transducers. External controllers are used in cases where global objectives beyond active damping are to be achieved.

3.1 Motivating Applications

The original motivation for the development of the integrated piezoelectric device was jitter reduction on spacecraft. The original space applications included: · *Spacecraft Solar Array Yokes*. Solar arrays are one of the relatively few sources of vibration on-board most spacecraft. In particular, the array drive motors or quasi-static thermal inputs initiate vibration of the arrays, resulting in application of forces to the rest of the spacecraft bus at frequencies corresponding to the natural modes of the arrays.

Other long structures are deployed or extended to support instruments, antennas, and sensors. Vibration of these booms can adversely affect other sensors on the booms or on the bus.

3.2. Device-Level Integration

The device-level integration employed is in contrast to other finer scales of integration. Larger structures such as aircraft skins might be created in the future using blended smart materials as a building block. Piezoelectric composites in which the piezoelectric component is distinguishable from the other constituents only on a very small scale are one example. In the context used here, mesoscale refers to discrete electromechanical components and devices rather than micromachined systems or blended materials and composites. Typical physical dimensions of constituents are measured in millimeters or centimeters and the overall device size is measured in centimeters.

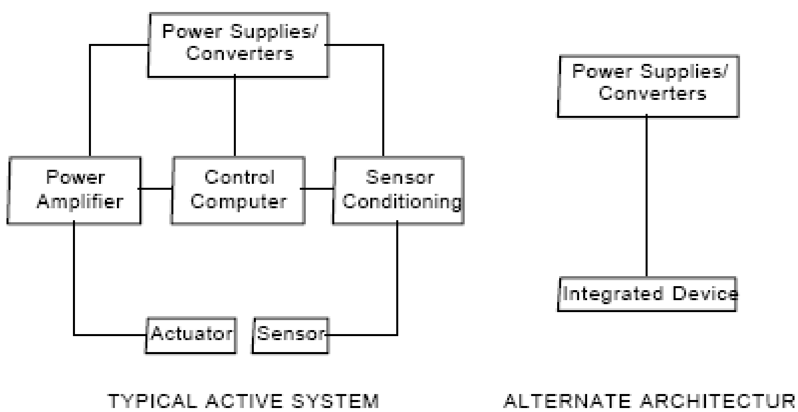

Figure 3: A simplified active vibration control system could integrate separate components into a single device

Smart materials introduce solid state means of transduction, provide a smooth energy transfer. Figure 3 compares the typical piezoelectric-based active system using separate components with a more fully integrated system.

The particular type of piezoelectric device suggested by Figure 3 is a low-profile system called a “patch” which can be bonded to the surface of a structure or embedded within a non-metallic structure.

3.3. Summary of Requirements and Design Goals

Requirements were established for the new device, including performance, system interfaces, and environmental compatibility. Environmental compatibility was considered in the contexts of space flight, clean room applications, industrial uses, and embeddability in composite or plastic structures. Specific requirements included:

· Achieve damping of z = 5-10% for a single mode

· Effective over frequency range from 10 Hz to at least 200 Hz

· Addressable by a digital computer and up to 10 parameters adjustable.

· Quiescent power less than 20% of peak power

· Standard temperature (-25C--55C) with possible extended operation

· Actuation material would be capable of 200 microstrain of elongation. (With a 50 mm actuator width and a 0.5 mm actuator height, this corresponds to approximately 300 N force.)

· No local modes below 500 Hz in frequency when device attached to or otherwise integrated with a structure.

4. DEVICE ARCHITECTURE

Fundamentally, the device transforms electrical power to influence mechanical systems. In order to accomplish this, there must be electromechanical coupling (the transducing subsystem) and electrical action (the electronic subsystem).

Figure 4 summarizes six of the physical layouts considered for the patch and its transducing and electronic subsystems. Layouts 2, 4, and 6 include soft layers to protect electronics from shock and vibration. The electronics section can be stacked on top of the transducer section (5 and 6) reducing substantially the parasitic non-actuation area. Connectors are a practical issue for any real-world device, as are manufacturing issues. The final device used layout 1, an architecture well-suited to initial development.

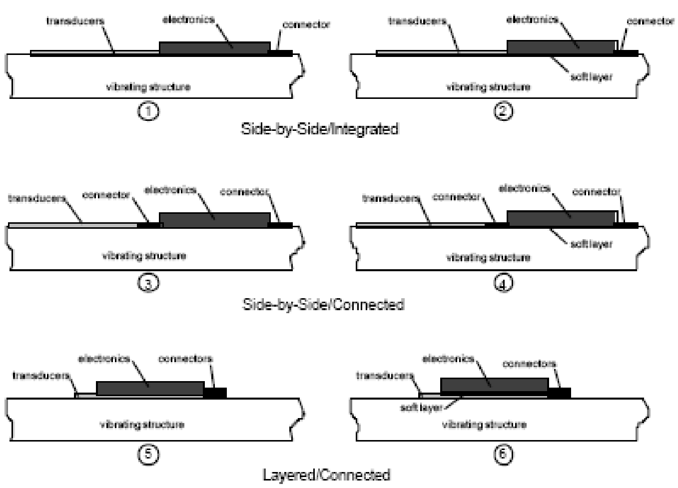

Figure 4: Options for layout of electromechanical transducing and electronic subsystems. Patches are shown bonded to the surface of a vibrating structure

Within the architecture of layout 1, there were several evolutions of the device. Table 2 summarizes the introduction of features during the patch development.

Table 2: Features added during each phase of the device Development

Phase 0	Phase A	Phase B	Phase C
Piezo actuator encapsulated in polyimid	One of two piezo layers used for sensing Sensor charge amp package built into device	Low-voltage multilayer actuator Separate sensor piezoceramics Power amp added to elec. package	Add control components to elec. package Electronics compacted to reduce volume

This section covers design of each subsystem. Actuation and Sensing are the two transducing functions. Signal Conditioning, Control, and Power Amplification are electronic functions. For vibration suppression applications, the actuator is perhaps the most critical element. The relative stiffness and total volume of the piezoelectric actuator determine the device authority over the vibrating structure. A single actuator with length and width in the low tens of millimeters is usually well suited to influence and damp modes with wavelengths in the range of tens of millimeters to hundreds of millimeters.

Materials. The actuator material governs the electromechanical energy conversion efficiency. Limited consideration was given to nonpiezoceramic materials such as lead magnesium niobate (PMN). PMN has been used successfully in stack type actuators for micropositioning and other applications.

Other piezoelectric forms such as polymer films have lower energy density and are unable to survive moderately high fabrication or operational heat inputs. Lead zirconate titanate (PZT) piezoceramic is the most common transducing material, and several compositions are available..

Multilayer Actuation. Multilayer actuators (MLAs) can provide the same amount of displacement and force capability as monolithic piezoceramics using less voltage and more current. For example, instead of a single 10-mil layer of PZT, a MLA uses four 2.5-mil layers. While the single layer might be operated at up to 200V, the four-layer system could produce the same response with 50V applied. The MLA approach was pursued in Phase B of the effort, with fabrication of a 28 V device. The experimental MLA fabricated for this project included 13 layers of PZT, each 38 microns thick. Individual electrodes within the stacked actuator were connected along one actuator edge. In the longer term, MLAs are promising, but several concerns arose during the development:

· *Electrode cost* For very thin PZT layers, the electrodes take up more of the total volume of the actuator and drive the cost.

· *Actuator size.* It is difficult to make larger multilayer actuators. 1 x 1 inch

· *Actuator thickness.* To reduce warping effects, 20 mils is close to the minimum feasible total thickness.

· *Layer thickness.* The minimum thickness is dictated by warping and wear-through during flattening operations.

· *Reliability.* The three-dimensional stress fields within the layers and the novelty of the processing steps make this an issue.

The electric field applied to the each of the *N* layers of a MLA is

$$E_3 = \frac{V_3}{t_{layer}} = \frac{NV_3}{t_a} \qquad (1)$$

where *V3* is the voltage, *ta* the total actuator thickness, *tlayer* the layer thickness, and electrode thickness is ignored. The applied electric field must be below the coercive field. A value of 800 V/mm (20 V/mil) is a conservative limit suitable for bipolar drive and operation. The voltage required to reach this field is :

$$V_3 = E_3 t_{layer} = \frac{E_3 t_a}{N} \qquad (2)$$

Using a larger number of layers to make up a given actuator thickness reduces the voltage requirement.

Table 1: Maximum voltages for different actuation layer thicknesses (assumes 800 V/mm max. field)

Layer Thickness		Max. Bipolar
microns	mils	Voltage (V)
250	10	200
200	8	160
150	6	120
100	4	80
50	2	40
38	1.5	30

The capacitance of the layered actuator is :

$$C^T = \frac{N^2 \varepsilon^T A_a}{t_a} \qquad (3)$$

where: *Aa* is the wafer area, and e*T* = k*T* e0, indicating a capacitance proportional to the square of the number of layers. The current requirement, considering the actuator as a capacitor only, is

$$I_3 = \omega C^T V_3 = \omega N \varepsilon^T A_a E_3 \qquad (4)$$

The current demanded increases with frequency, the dielectric constant of the material, the size of the patch, the applied field, and the number of layers. Voltage-strain hysteresis curves for one MLA specimen are shown in Figure 5. The maximum voltage shown is 18 V peak.

Tests of five MLAs showed an effective *d*31 coefficient of 239 pm/V at 4.5 V input, 266 pm/V at 9.1 V input, and 321 pm/V at 18.2 V input. An actuation subsystem using two MLAs was incorporated into the Phase B prototype patch. Three possible classes of wafer actuator/sensor configurations are summarized in Table 2. Configuration (a) places the transducers sideby- side on the surface of the structure. In configuration (b) the sensor is stacked directly above the actuator. In configuration (c) a single piezoelectric functions as both sensor and actuator. In any case, the overall size of the sensor should be the size of the actuator or smaller. The sensor length and width should be significantly greater than the thickness.

Table 2: Comparison of options for actuator-sensor integration

Issue	A: Side-by-side	B: Stacked	C: Single trans.
Use of surf. area	Inefficient	Efficient	Efficient
Collocation	Not perfect	Perfect	Perfect
Local strain	Possible problem	Signif. concern	Signif. concern
Other issues	Asymmetry	Shielding	Mismatched bridge

Other properties were considered desirable in the sensor:

· *Compatibility with actuation*.
· *Low noise*. .
· *Predictable response characteristics*.
· *Low cost*.

A finite element model was developed to aid the sensor pair location decision.

The model included a piezoceramic actuator surrounded by a softer plastic material on the surface of a beam. The model was run to determine how closely the sensors could be placed to the actuators and still avoid large local stresses induced by the actuation.

Figure 5 shows a representative plant transfer function and the SRF compensator

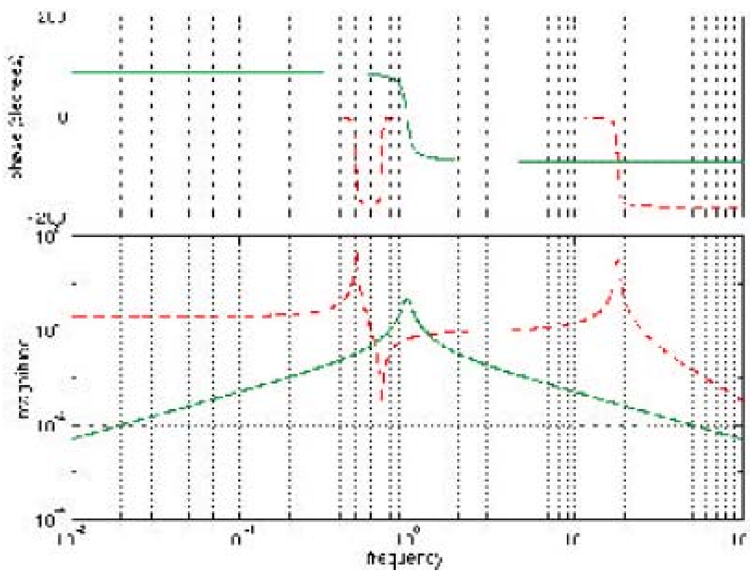

Figure 5: Example sensor-actuator transfer function (dashed) and an SRF compensator (solid)

SRF is a second-order control law of the form:

$$V_{act}(s) = \frac{g\omega f^{\,s}}{s^2 + 2\zeta_f \omega_f s + \omega_f^2} V_{sesn}(s) \qquad (5)$$

Vsens(*s*) is the sensor voltage as a function of the Laplace variable *s* and *Vact*(*s*) is the voltage output to the piezoceramics. The control law is a function of the controller gain, *g*, the natural frequency of the filter, w*f*, and the nondimensional damping ratio, *zf*

Positive position feedback (PPF) is a control law of the form:

$$V_{act}(s) = \frac{g\omega^2 f}{s^2 + 2\zeta_f \omega_f s + \omega_f^2} V_{sesn}(s) \quad (6)$$

The three parameters for the PPF filter are the same as for the SRF compensator. The primary difference between the two compensators is that SRF rolls off with a slope of -20 dB/decade at frequencies above the resonance pole and PPF rolls off with a slope of -40 dB/decade.

Table 4: Comparison of 4 power amplifier options

	Integrated	Discrete
Linear	Compact, proven, concentrated heat source	Low-cost, greater volume, better heat distribution
Switcher (PWM)	Efficient, costly, concentrated heat source	Unproved, better heat distribution

Packaging and Fabrication

The fabrication technology matured considerably during the development. This section describes key motivation and design considerations.

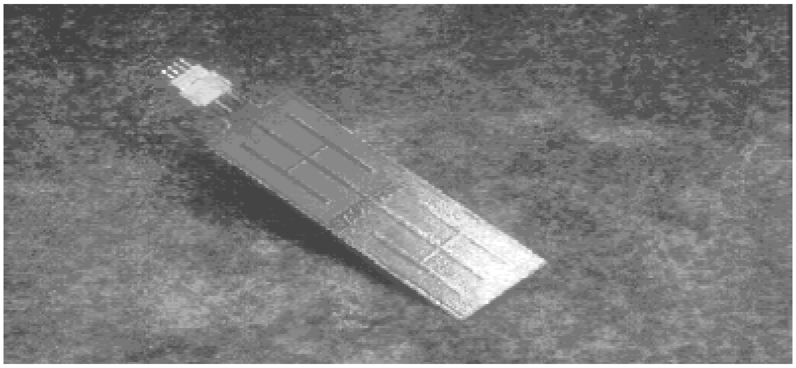

Figure 6: The QuickPack design was used as the basis for the device transducer package.

Figure 6 shows an existing package built around four 0.010 inch piezoceramic sheet actuators located at two stations.

5. CONCLUSION

This paper has summarized development of a piezoelectric-based electromechanical device useful for suppression of vibration and noise. The device is representative of a broader technology which combines piezoelectric transducers and electronic components in efficient, low cost packaging. The motivation and requirements for the specific device were elaborated. Each of five functional subsystems - actuation, sensing, sensor conditioning, control, and power amplification – was discussed. The devices constructed used available piezoceramic wafers for actuators and sensors, but prototype devices were constructed using novel low-voltage multilayer actuators and actuators with interdigital electrodes.

Packaging considerations were discussed. Test results indicating the vibration suppression performance and device programmability were presented. The devices are one example of an integration technology which can be adapted to a variety of applications.

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