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# Biologically Inspired Controller for Sound Applications

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**A biologically inspired control approach for reducing radiated sound power from distributed elastic systems has been experimentally verified for harmonic, narrowband excitation. The control paradigm approximates natural biological systems for initiating movement, in that a small number of signals are sent from an advanced, centralized controller (analogous to the brain) and are then distributed by local rules and actions to multiple actuators (analogous to muscle fiber). The controller was applied to attenuate radiated sound power from a plate. Experimental investigations of two different local learning rules, the phase variation and optimal methods, were carried out. Performance of the various methods decreased radiated sound power from a clamped plate by up to 16 dB for harmonic off-resonance excitation and up to 22 dB for on-resonance excitation. In general the results have demonstrated that the biological control approach has the potential to control multimodal response in distributed elastic systems using an array of many actuators with a reduced-order main controller. Thus significant reductions in control system computational complexity have been realized by this approach.**

## Nomenclature

$J$ = cost function
$M$ = number of microphones
$v$ = error sensor voltage
$\gamma$ = "slave" actuator complex gains
$\mu$ = convergence parameter

## I. Introduction

RECENT work has demonstrated the potential of active control of distributed elastic systems using multiple, independent actuators and sensors. In work concerned with the control of sound radiation from vibrating panels, the importance of number of channels of control and optimization of the transducer position and shape has been demonstrated.[1] However, these investigations were carried out for a fixed frequency, and it is apparent that for good control over a bandwidth of frequencies the control actuators and sensors need to be adaptive in shape. At first sight this problem could be solved using an overall transducer broken up into many individual small elements, each connected by an individual control channel. In this situation the control transducer would effectively reoptimize its configuration for different conditions by adaptively weighting each transducer segment. Meirovitch and Norris[2] have demonstrated the advantage of such an approach by considering fully distributed control in reducing control spillover. The disadvantage of this approach is that, for systems with a high modal density, the number of actuators and sensors required becomes extremely large. A high number of control channels has a number of problems mainly associated with memory requirements and computational time in the hardware systems used to implement the control. In addition, collinearity of transducer transfer functions (i.e., the transducer transfer functions are not fully linear independent) causes stability problems in systems with a high number of transducers.

A new approach of controlling distributed elastic systems is presented. The approach is inspired by the action of biological natural systems where a small number of main signals are transmitted from the brain to a large area of muscle tissue to activate many independent segments of muscle. The signals then stimulate local action that is governed by, for example, chemical interaction of locally connected nerves, etc., resulting in multiple subsequent signals for individual muscle cell elongation or contraction. Put simply, a signal is sent from a central complex processor (the brain) and then is broken into multiple signals by local simplified control rules (muscle cells, etc.).[3]

This paper details an experimental implementation of such a process applied to radiated sound power control, which has been previously studied in a limited analytical investigation,[4] whereas a more complete theoretical development and experimental implementation to control beam vibration is presented in Carneal and Fuller.[5] A distributed elastic system is harmonically excited and controlled by multiple control inputs. In the biologically inspired (BIO) control approach, one control input is chosen as the "master" and is under direction of the main, centralized advanced controller. The other "slave" inputs derive their control laws by localized, simple learning rules related to the behavior of their neighbor actuators and are independent of the main controller direct signal, as seen in Fig. 1.

In the following sections, the experimental investigation is discussed, including performance metrics, experimental setup, and procedure. Results are presented for two excitation frequencies, one off resonance and one on resonance, followed by concluding remarks.

## II. Experimental Investigation

### A. Experimental Setup

#### 1. *Controller*

The BIO controller was programmed on a TMS320C30 digital signal processor (DSP) mounted in a 80386 33-MHz personal computer (PC). To increase the maximum sampling rate, the number of operations performed by the DSP was minimized. Therefore, the input/output (I/O) functions, the cost function, and FIR filter calculations were performed on the DSP, whereas the controller logic was performed on the PC and communicated to the DSP. The sample rate for the controller was set at 10 times the pure tone excitation frequency with each cost function consisting of 250 time sample points, leading to an update for the finite impulse response (FIR) filter approximately every 0.05 s at a sampling frequency of 5000 Hz. Figure 2 shows a schematic of the experimental setup of the BIO controller.

Again referring to Fig. 2, the BIO control algorithm is discussed. For the "master channel only" case, the adaptive gains $\gamma$ were set to zero, rendering the control algorithm as a single output system. For the phase variation method, the master channel was allowed to converge, and then the FIR filter was locked at its optimum value. The master channel FIR filter coefficients were applied to the slave control channel, one by one, alternating left then right of the master control channel. The filter coefficients were tried in phase

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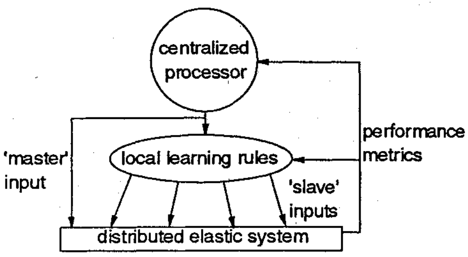


**Fig. 1 Biological control approach.**

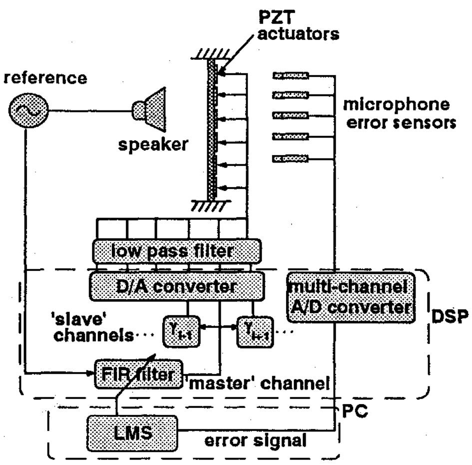


**Fig. 2 Schematic of radiated sound power experiment.**

($\gamma = +1$), out of phase ($\gamma = -1$), or turned off ($\gamma = 0$) while the cost function $J$ was sequentially observed for each change. The gain $\gamma$ that resulted in the lowest cost function was kept, the cost function was measured, and the process was applied to the next slave control channel until all slave control paths were progressively tested.

For the optimal distributions, the adaptive gains $\gamma$ were predetermined from experimental data (as outlined in the next paragraph) and then scaled relative to the master actuator. The gains were entered to the control program before its execution. Once the FIR filter update equation was invoked, the master channel FIR filter was updated as for the "master" only case. However, before the digital-to-analog (D/A) conversion process was performed, the master channel FIR filter coefficients were multiplied by the adaptive gains $\gamma$, thereby generating the slave control outputs. When the D/A process was triggered, the master and slave control signals were output simultaneously.

It was stated in Carneal and Fuller,[5] the gains $\gamma$ can be determined analytically or experimentally. For vibration control, the optimal distribution gains were determined analytically using adaptive feedforward control theory.[5] However, for the radiated sound power experiment, the optimal distribution gains $\gamma$ were determined experimentally from a full-order time-averaged-gradient (TAG) least-mean-squares (LMS) algorithm, where each output channel was fully independent of any other output channel (as compared with the master/slave relationship of the BIO controller). Since the controller uses a time-averaged gradient, the FIR filters do not converge simultaneously like the filtered-X LMS.[6] Instead, the cost function is minimized by each channel separately, while the controller indexes the channels sequentially. By determining the gains $\gamma$ experimentally, it can be shown that the BIO controller can be applied to complex structures where no analytical solution for the gains $\gamma$ is readily available.

The experimental procedure for determining the gains $\gamma$ is outlined as follows: Once the full-order LMS controller had converged, the FIR filter weights were recorded and converted into complex gains. These gains were then scaled so that the master gain was 1. The scaled gains were then input to the BIO control algorithm before the invocation of the FIR filter update equation.

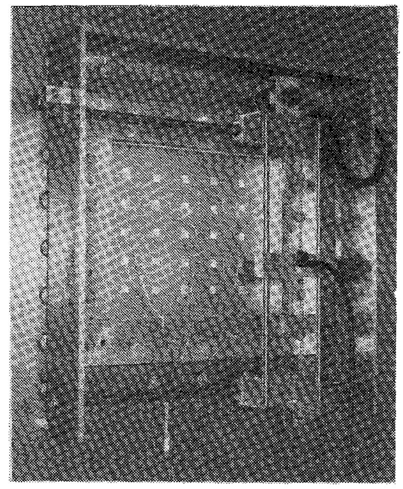

**Fig. 3 Photograph of radiated sound power experiment.**

*2. Radiated Sound Power Control*

To experimentally verify the BIO controller applied to radiated sound power control, we performed an experiment on a plate made of aluminum of length 0.380 m, width 0.300 m, and thickness 0.0031 m. A photograph of the experimental setup is shown in Fig. 3. The plate was mounted in a common wall between a reverberant chamber and an anechoic chamber. The mounting apparatus clamped the plate at the boundaries (which allowed negligible rotation of the boundary and negligible transverse displacement) to approximate clamped boundary conditions. Harmonic, narrowband excitation was provided by an approximation of an oblique plane wave from a speaker in the source (reverberant) chamber placed at 45 deg from the plate normal. The speaker was placed at 0.250 m from the plate so that the direct radiated field dominated the input. Experiments were performed at excitation frequencies of 319 Hz, which is off resonance between plate mode (1, 1) and (2, 1), and 397 Hz, which is the plate mode (2, 1) resonance.

Error signals were provided by the output of five microphones mounted in a hemispherical configuration in the receiving (anechoic) chamber, which was experimentally determined to have a cutoff frequency of approximately 300 Hz. The microphones were placed according to equal area calculations of a hemisphere. To approximate a cost function of radiated sound power, a sum of the mean square voltage read from the microphones was provided to the LMS algorithm (and the phase variation method of the BIO controller). The cost function at time step $t$ is defined as

$$J_t = \sum_{i=1}^{M} |v_i|^2 \tag{1}$$

where $v_i$ is the microphone voltage, subscript $i$ indicates the microphone number index, and $M$ is the total number of microphones.

Control inputs were provided by six ceramic piezoelectric (PZT) patches, each having dimensions 0.064 m long $\times$ 0.038 m wide $\times$ 2.59$E$-04 m thick. The PZT patches were directly bonded to the plate at evenly spaced central locations forming a 3 $\times$ 2 grid on the plate. Difficulties associated with providing a good seal between the source and receiving chambers demanded that the PZT actuators were bonded to one side of the plate only, instead of the usual PZT pair.

It should be noted that the use of a hierarchical control structure has some important considerations as far as the system characteristics are concerned. In the phase variation method, the "slave" actuators are "turned on" sequentially. In the optimal distribution, the "master" and "slave" actuators form a single "distributed" actuator that does not allow adjustment of the "master" and "slave" actuators' relative magnitude and phase. Therefore the system appears underdetermined (i.e., six actuators and five error sensors), when actually the system is overdetermined (i.e., one actuator and five error sensors) since only one control channel is being updated at any time.

### B. Performance Metrics

Performance of the control algorithm was defined as the reduction in the cost function as

$$\text{reduction(dB)} = 10\log_{10}\left(\frac{J_{\text{uncontrolled}}}{J_{\text{controlled}}}\right) \qquad (2)$$

where $J_{\text{uncontrolled}}$ is the uncontrolled cost function, and $J_{\text{controlled}}$ is the controlled cost function.

For a more detailed analysis of the response of the elastic system, a laser vibrometer was used to determine the out-of-plane vibrational characteristics for the uncontrolled and controlled cases. Transverse vibrational measurements were taken at 25 evenly spaced locations that formed a $5 \times 5$ point grid on the plate described earlier.

### C. Experimental Procedure

The experimental procedure for the master and phase variation test case was as follows: First, the disturbance was turned on. The control program was initialized: the dimensionless convergence parameter $\mu$ was set at approximately 0.01, the master control channel was set to the desired value, and the sampling frequency was set at 10 times the excitation frequency. The uncontrolled elastic system out-of-plane vibrational velocity was then measured using the laser vibrometer, and the uncontrolled cost function was measured. After the invocation of the control algorithm, the master control channel was allowed to converge, and the cost function and the elastic system vibration were measured for the "master" case. The phase variation algorithm was invoked, and after completion, the cost function and the elastic system vibration were measured for the "phase variation" case. The controller was then turned off.

For the optimal distribution, the disturbance was set at approximately the same level. The control programs were initialized: the convergence parameter $\mu$ was set at approximately 0.01, the master control channel was set to the desired value, and the sampling frequency was set at 10 times the excitation frequency. Uncontrolled elastic system vibration and cost function were then measured. After the controller was started and allowed to converge, the elastic system vibration and cost function were measured for the controlled case.

## III. Results

An extensive experimental investigation was performed; however, for brevity, only select results are presented. It should be noted that the results presented are indicative of the overall trends observed, and in general, the stated conclusions apply to all of the results attained. Experimental results are presented for two different excitation frequencies: one off resonance (319 Hz) and one on resonance (397 Hz).

### A. Selection of Master Actuator

As stated earlier, the selection of the master actuator could be done using a simple search scheme. When the BIO controller was analytically applied to beam vibration control, the influence of the master actuator on phase variation performance was determined analytically.[5] However, for this experimental investigation, the influence of the master actuator on phase variation performance was determined experimentally. Performance of the master actuator and the phase variation method (including the control string) is shown in Tables 1 and 2 for the off-resonance and on-resonance test cases, respectively. The control string of the phase variation method denotes the final implementation of the slave control channels, where 0 indicates off, $\oplus$ indicates the master control channel (which is by definition in phase), + indicates channels implemented in phase, and − indicates channels implemented out of phase.

As seen in Table 1, the off-resonance master test performance varies from a low of 0.0 dB for actuator no. 4 to a high of 3.8 dB for actuator no. 5. The performance with the phase variation method ranges from a low of 0.7 dB for actuator no. 4 to a high of 12.4 dB for actuator no. 1. Note that for four actuators the increase in performance was greater than 6 dB, which indicates that the phase variation method is effective when applied to structures that have a multimodal response, i.e., complex structures or structures excited off resonance. Using the results of Table 1, actuator no. 1 was chosen to be the master actuator for the off-resonance test since that actuator best exhibited the capabilities of the phase variation method and had marginal control performance by itself.

**Table 1 Influence of master actuator on phase variation performance (319 Hz, off resonance)**

| Master actuator no. | Master performance, dB | Phase variation performance, dB | Control string[a] |
|---|---|---|---|
| 1 | 0.6 | 12.4 | $\oplus - + + - 0$ |
| 2 | 2.8 | 10.0 | $- \oplus - - + 0$ |
| 3 | 0.3 | 4.5 | $+ - \oplus + - +$ |
| 4 | 0.0 | 0.7 | $+ - + \oplus - +$ |
| 5 | 3.8 | 11.6 | $- + 0 - \oplus -$ |
| 6 | 0.3 | 7.8 | $+ - + + - \oplus$ |

[a] $\oplus$ indicates the master control channel.

**Table 2 Influence of master actuator on phase variation performance (397 Hz, on resonance)**

| Master actuator no. | Master performance, dB | Phase variation performance, dB | Control string[a] |
|---|---|---|---|
| 1 | 17.7 | 17.8 | $\oplus - 0000$ |
| 2 | 0.0 | 0.0 | $0 \oplus 0000$ |
| 3 | 16.4 | 18.4 | $0 + \oplus 0 + 0$ |
| 4 | 17.5 | 17.5 | $000 \oplus 00$ |
| 5 | 0.0 | 0.0 | $0000 \oplus 0$ |
| 6 | 17.6 | 21.2 | $0 + 00 + \oplus$ |

[a] $\oplus$ indicates the master control channel.

**Table 3 BIO controller performance**

| Excitation frequency, Hz | 319 | 397 |
|---|---|---|
| Resonance | No | Yes |
| Mode | —— | (2, 1) |
| Master actuator no. | 1 | 6 |
| Master, dB | 0.6 | 17.6 |
| Phase variation, dB | 12.4 | 21.2 |
| Control string[a] | $\oplus - + + - 0$ | $0 + 00 + \oplus$ |
| Optimal, dB | 15.6 | 21.6 |

[a] $\oplus$ indicates the master control channel.

The on-resonance master test performance, shown in Table 2, varied from a low of 0.0 dB for actuators nos. 2 and 5 to a high of 17.7 dB for actuator no. 1. The performance with the phase variation method ranged from a low of 0.0 dB for actuators nos. 2 and 5 to a high of 21.2 dB for actuator no. 6. The aforementioned results conclude that the phase variation method was able to increase control performance even when the system was excited on resonance, which is due to the relatively high modal density of a plate. Note that the poor performance of actuators nos. 2 and 5 was due to their inability to couple into the (2, 1) mode due to their placement on a node line of that mode. Using these results, actuator no. 6 was chosen to be the master actuator for the on-resonance test.

### B. Off-Resonance Performance

The relative performance for control with the "master" actuator only (referred to as master), the phase variation, and the optimal distribution method are compared for off-resonance excitation. For these experiments, the excitation frequency was 319 Hz, the master actuator was PZT no. 1, and the sampling frequency was 3000 Hz.

As seen in Table 3, the master case displays poor control performance of 0.6 dB. The modal decomposition, seen in Fig. 4, shows no decrease in the (1, 1) mode and significant increases in the other modes. It is evident that actuator no. 1 cannot couple into the plate vibration at this frequency, leading to significant spillover into several modes.

While maintaining the control system simplicity of one control channel, the BIO controller using the phase variation method shows admirable control performance of 12.4 dB as seen in Table 3. In addition to the master actuator (PZT no. 1) implemented in phase,

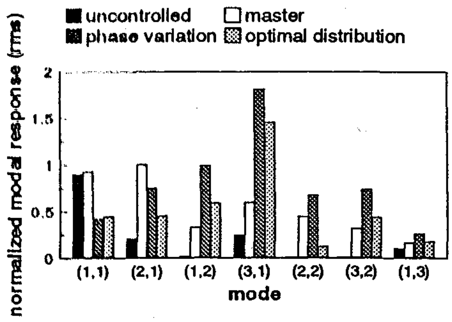


**Fig. 4 Modal response of plate excited off resonance.**

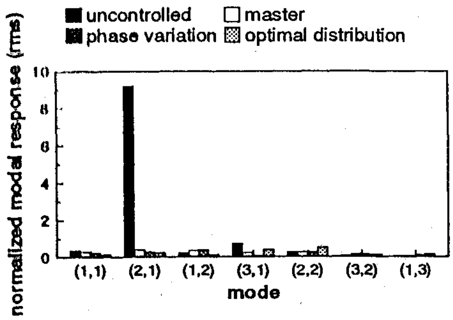


**Fig. 5 Modal response of plate excited on resonance.**

there were two slave control actuators implemented out of phase and two implemented in phase, as seen in the control string. As seen in Fig. 4, the addition of the slave actuators reduced the response of the (1, 1) mode, which is the most efficient acoustic radiator below the critical frequency. The increase in performance is a direct result of the reduction in the response of this mode. Increases in response are seen in other modes; however, these are significantly less efficient acoustic radiators than the (1, 1) mode, and therefore performance remains good. It is evident that the phase variation method was able to construct a distributed actuator that could couple effectively into the plate vibration, thereby reducing the response of the most efficient acoustic radiator.

The optimal distribution shows good control performance of 15.6 dB, as seen in Table 3. The modal decomposition in Fig. 4 shows a significant reduction in the (1, 1) mode with less spillover into the other modes, which results in increased control performance compared with the phase variation method. It is obvious that the distributed actuator formed by the optimal distribution couples into the plate vibration even better than the phase variation method, although a priori knowledge is required.

### C. On-Resonance Performance

In this section, the relative performance for control with the "master" actuator only (referred to as master), the phase variation, and the optimal distribution method are compared for on-resonance excitation. For these experiments, the excitation frequency was 397 Hz, the master actuator was PZT no. 6, and the sampling frequency was 4000 Hz.

It is not surprising to see the good performance of the master case when the plate is excited on resonance, which shows a reduction in cost function of 17.6 dB in Table 3. As seen in Fig. 5, the master actuator was able to reduce the response of the (2, 1) mode to the level of the other modes. With the implementation of the phase variation method, control performance increased to 21.2 dB, as shown in Table 3. With the response of the modes nearly equal, the addition of the slave actuators slightly reduced the response of the (1, 1) and the (2, 1) modes as seen in Fig. 5, which resulted in increased performance. The distributed actuator formed by the optimal distribution has slightly better performance than the phase variation method by 0.4 dB as seen in Table 3. Figure 5 shows the reduction of modes (1, 1) and (2, 1) was slightly better than the phase variation method.

The previous results indicate that even in on-resonance situations, where the resonant mode can theoretically be controlled with one actuator,[2] increases in control performance can be attained with the addition of slave actuators. This can be attributed to the high modal density of the plate. However, the addition of the actuators results in diminishing returns in performance.

## IV. Conclusions

A biologically inspired control approach for reducing radiated sound power from distributed elastic systems has been experimentally verified for narrowband excitation. The control approach, inspired by biological systems, approximated the control structure used with biological muscle, where a few main control signals were sent from an advanced, centralized controller (the brain) and distributed by local rules and action to multiple actuators (muscle tissue). Experimental investigations of the performance of two different variations of local learning rules, the phase variation and optimal methods, were carried out.

Performance of the various methods decreased radiated sound power from a clamped plate by up to 16 dB for harmonic off-resonance excitation and up to 22 dB for on-resonance excitation. The addition of the slave control actuators was seen to increase control performance even for on-resonance excitation, due to the high modal density of the plate. However, the addition of actuators resulted in diminishing returns in performance.

In general, the results demonstrated that the biological control approach has the potential to control multimodal response in distributed elastic systems using an array of actuators with a reduced-order controller. Thus, significant reductions in control system computational complexity have been realized by this approach. Future work will concentrate on additional local learning rules and theoretical application to two-dimensional distributed elastic systems.

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