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Active Vibration Control of Structures using an Impedance Matching Control Technique

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ABSTRACT

Active vibration control of structures has gained a lot of interest in recent years. This paper presents an active vibration control methodology of a structure using piezoelectric actuators. The proposed methodology is useful in practical applications where the system to be controlled is difficult to model due to the presence of complex boundary conditions. The impedance matching control technique uses a power flow approach wherein the controller is designed such that the power flow into the structure is minimized. The system transfer function is obtained from the experimental collocated actuator/sensor pair data using Eigen Realisation Algorithm (ERA). The controller is designed for the system transfer function according to impedance matching theory. The above approach is targeted towards the vibration control of wind tunnel stings, which suffer from flow-induced vibration. A wind tunnel sting model is designed and fabricated for this study. The real time implementation of the impedance matching controller has been carried out using dSPACE® Digital Signal Processor (DSP) card. The results are encouraging and demonstrate the feasibility of applying this technique in the wind tunnel.

Keywords: vibration control, impedance method, de-reverberated transfer function, piezostack actuator, digital signal processor and collocated sensor/actuator

1. INTRODUCTION

Smart actuators and intelligent structures have received considerable attention in the field of aerospace to realize new functions or more efficient functions from passive structures. Active vibration control systems for structural vibration comprises sensors, control software/hardware, control force generator/actuator, which act as an integral system[1].

Vibration control of structures has gained wide attention especially with the advent of smart materials, on account of its well-known benefits. One of the potential applications is control of Wind tunnel stings, which suffer from flow-induced vibrations. These vibrations could damage the balance and affect data. In order to prevent this, high capacity balances are usefully used and the sting is over designed. This inturn imposes restrictions on usable Mach numbers in the wind tunnel. Thus by controlling the vibrations in the model support structure, low capacity balances can be used to expand the capabilities of the wind tunnel.

The impedance control method is based on the electrical circuit analogy that for maximum power dissipation in the circuit, the load impedance should be equal to the complex conjugate of the source impedance[2, 3]. The mobility and its inverse, the impedance, are considered because the product of the input and the output of these transfer functions is the power flow. A dereverberated transfer function (DTF), as opposed to the reverberated transfer function (RTF), is devoid of the poles and zeros[4]. The DTF is obtained from the RTF through an approximate method, by critically damping the poles and zeros of the RTF[4]. This study uses the above-mentioned method on account of its simplicity and ease of application in practical situations. The details about this method were presented in our earlier paper[3].

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This paper presents a study on active control of vibrations of wind tunnel model structures using piezo stack actuators. This work demonstrates an implementation of a control methodology that has many advantages for practical and realistic applications. For realizing the aim of this project an idealized wind tunnel sting model was designed and fabricated. Two CEDRAT® Parallel Prestressed Actuators (PPA60L) were used. Simulations of the open loop and the closed loop responses were carried out in MATLAB® Simulink followed by real time experiments[5]. The real time experiments were conducted to obtain collocated (actuator/sensor pair) open loop response using dSPACE® DS1102 digital signal processor (DSP) card and MATLAB® and the transfer function of the wind tunnel sting model was estimated using ERA method. From the system transfer function, the controller was designed according to impedance matching theory. Closed loop experiments were carried out to implement the vibration control methodologies on the idealized wind tunnel sting model and the results are presented here.

2. IMPEDANCE CONTROL

The impedance control method minimizes the power flow into the system and thus controls the structure. The principle of impedance control is that, for maximum power dissipation, impedance of the controller(Z_c) should match the complex conjugate of the structural impedance(Z_s^*), i.e.

$$Z_c = Z_s^* \tag{1}$$

The theoretical development of the impedance control method is explained in the previous studies[3]. However, this controller is not realizable in practice due to its non-causal nature. An approximation to Z_s^* is obtained by critically damping the poles and zeros of Z_s[4]. An important requirement is that the actuator-sensor pair for which the Z_s is obtained has to be a collocated pair. This can be understood as a requirement where only the local dynamics is modeled or the power flow at the actuator location is desired.

Usually the plant transfer function is obtained from theoretical models such as finite element models. However, this might be a cumbersome and difficult requirement for structures that are complex and are made up of many sub-assemblies. Thus, keeping the practical requirements in consideration, the impedance transfer function is obtained from experiments. To obtain the transfer function from experiments, a robust system identification method is required wherein the effects of noise and other disturbances are negated. In this study, the system identification is done using an Eigen Realisation Algorithm whose details are given in the following section.

3. SYSTEM IDENTIFICATION

In order to design a controller for a structure it is necessary to have a mathematical model of the system (sting model) that adequately describes the system dynamics. There are different methods to obtain this state space model, such as Auto Regressive methods and Eigen Realisation Algorithm[6] (ERA). The ERA technique is detailed here, which is used in this study to obtain the transfer function from the experimental data. The eigensystem realization algorithm is implemented for model parameter identification and model reduction of dynamic systems from test data[6, 7]. The approach is introduced in conjunction with the singular value decomposition technique to derive the basic formulation of minimum order realization, which is an extended version of Ho-Kalman algorithm. The basic formulation is then transformed into modal space for modal parameter identification.

The process of constructing a state space representation from experimental data is called system realization. Ho and Kalman showed that the minimum realization problem is equivalent to a representation problem involving a sequence of real matrices known as Markov parameters (pulse response functions). By minimum realization it is meant a model with the smallest state space dimension among systems realized that has same input-output relations within a specified degree of accuracy[6, 7]. The eigensystem realization algorithm consists of two major parts, namely, basic formulation of the minimum-order realization and modal parameter identification.

The computational steps of ERA can be summarized as follows

1. Construct a block Hankel matrix H(0) by arranging the Markov parameters (pulse response samples) into blocks with given α,β
   Where,
   $\alpha, \beta \rightarrow$ integer $\geq n$
   $n \rightarrow$ order of Hankel matrix
2. Decompose H(0) using singular value decomposition.
3. Determine the order of the system by examining the singular values of the Hankel Matrix H(0)
4. Construct a minimum order realization [A,B,C] using a shifted block Hankel Matrix H(1)
   A,B,C → minimum realization

5. Find the eigensolution of the realized state matrix and transform the realized model to modal coordinates to calculate the system damping and frequencies

Note that the optimum determination of α,β in step 1 requires some engineering intuition. This determination is related to the choice of the measurement data to minimize the size of the Hankel matrix H(0) with the rank unchanged.

From the computational standpoint, the algorithm is attractive since only simple numerical operations are required. The computational procedure is numerically stable. The structural dynamics requirements for modal parameter identification and control design requirements for a reduced state space model are satisfied. Data from more than one test can be used simultaneously to efficiently identify closely spaced eigenvalues. Thus obtained model parameters are used to design the controller for closed loop control.

4. TRANSFER FUNCTION ESTIMATION

An experimental study was conducted with the Wind Tunnel Sting Model to extract the transfer functions and to study the characteristics of the Sting. Two CEDRAT PPA60L stack type piezo actuators are mounted between base plate and aluminum blocks. The conventional foil type strain gauge (sensor) is mounted on the Aluminum block bonded to the top of each of the actuators, to measure the structural strains. Initially, the piezo stacks are screwed to the bottom plate. The top plate is placed on the shaft and a bolt is tightened to get the required preload and to fix it firmly to the shaft. The sting is then assembled with the base flange. The pictorial view of the experimental setup is shown in figures 1 and 2.

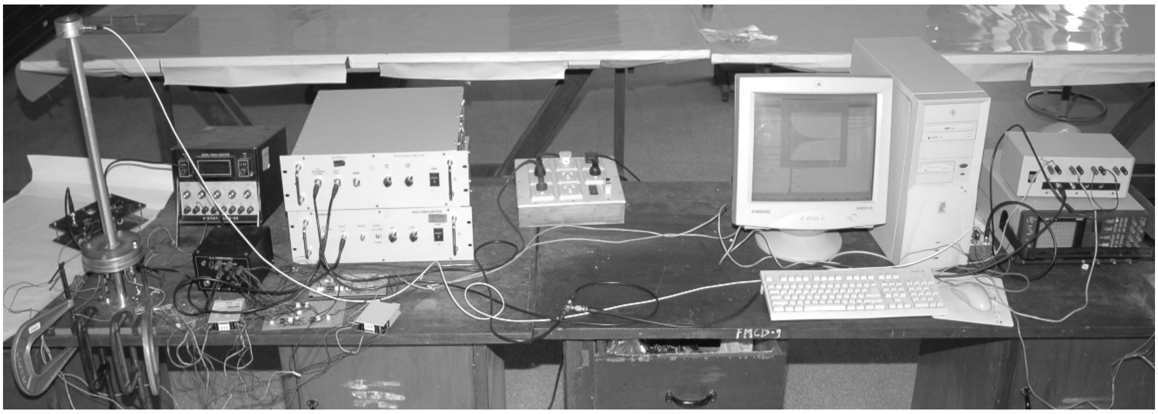

Figure 1. Experimental setup

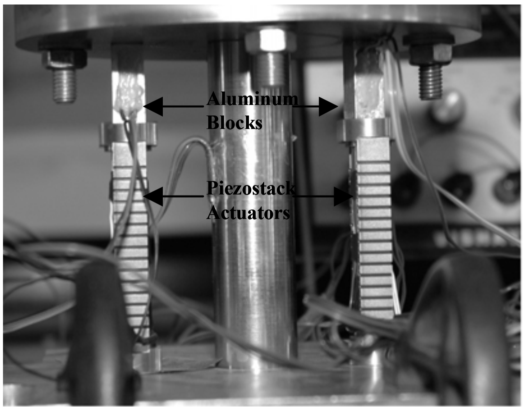

Figure 2. Closer view actuator sensor pair

The real-time experiments on the sting is carried out using a dSPACE® digital signal processing (DSP) card[8]. The card is based on a Texas Instruments TMS320C31 floating-point digital signal processor (DSP), which forms the main processing unit, providing fast instruction cycle time for numerically intensive algorithms. The board also has a set of onboard peripherals such as Analog to Digital Converters (ADC), Digital to Analog Converters (DAC) and a timer, which are frequently used in digital control systems. The 12-bit and 16-bit ADC's are capable of 800KHz and 250KHz-sampling speeds respectively with an input signal measurement range of ±10V. The DSP card acquires analog signals from the piezoelectric sensor through the ADC. Raw sensor outputs are appropriately conditioned before feeding to the DSP card. The output from the controller as computed by the DSP card is amplified using a power amplifier before feeding it to the piezoelectric actuator. The control algorithm is coded using MATLAB/SIMULINK® [5] and downloaded onto the DSP card using a MATLAB®-dSPACE® interface.

It should be noted that the voltage to be applied to the actuator can only lie between –20V and 150V for the Parallel Prestressed Actuator (PPA), However, for dynamic applications, an A/C (sinusoidal) signal is necessary, and with the constraints of the voltage mentioned above, this is only possible by having the sinusoidal signal with DC biased voltage. The signal then fluctuates between –20V and 150V. In order to achieve this, a special amplifier was developed, which accepts a ± 10V sinusoidal signal from a Digital to Analog Converter (DAC) of the DSP card then amplifies the signal to ± 100 V with a variable DC bias of 100 V.

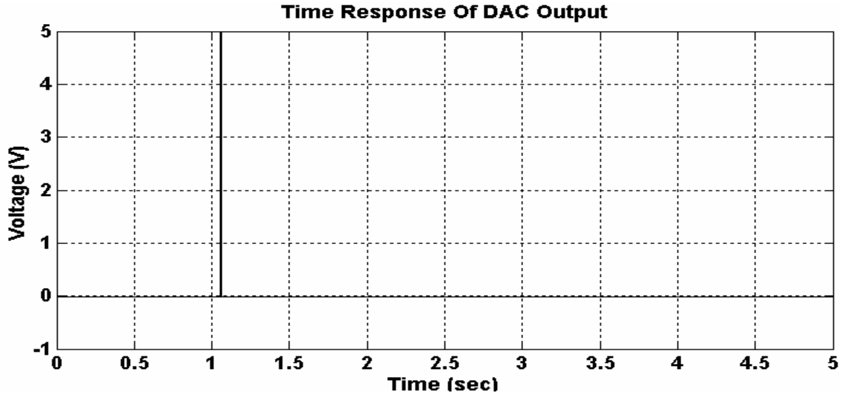

Figure 3. DAC output / controller output

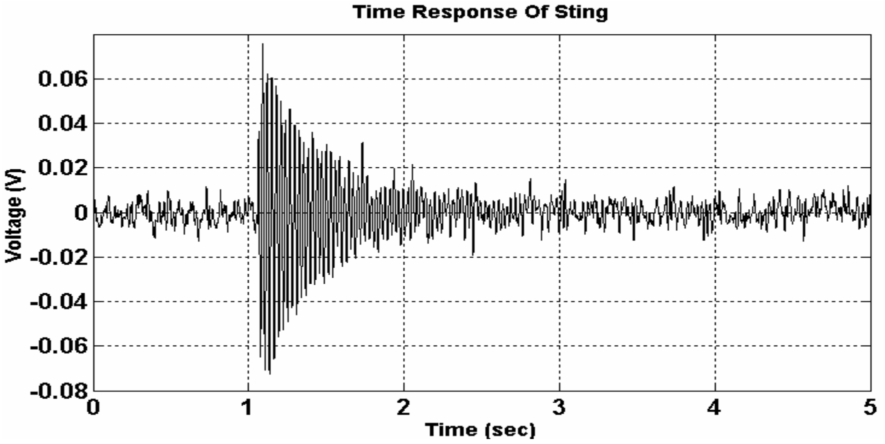

Figure 4. Open loop response

The experiments were conducted with the help of SIMULINK®-dSPACE® interface. An impulse signal (shown in figure 3) with amplifier gain was input to the sting and response of the sting was measured using the strain gauge mounted on the aluminum blocks. The strain gauge output is continuously monitored through ADC and stored in computer as shown in Figure 4. The transfer function is estimated from the impulse response shown in Figure 4 by using the Eigen Realisation algorithm (ERA) as explained in the previous section. The estimated transfer function with unit gain obtained was

$$TF = \frac{14.72}{s^2 + 7.143s + 4.428e004} \tag{2}$$

The impulse response of the above transfer function is simulated and compared with the experimental results. It can be seen from figure 5 that the simulated response agrees well with the experimental response although with a small phase lag. Hence the estimated system transfer function can be used to obtain the controller transfer function using impedance matching control technique.

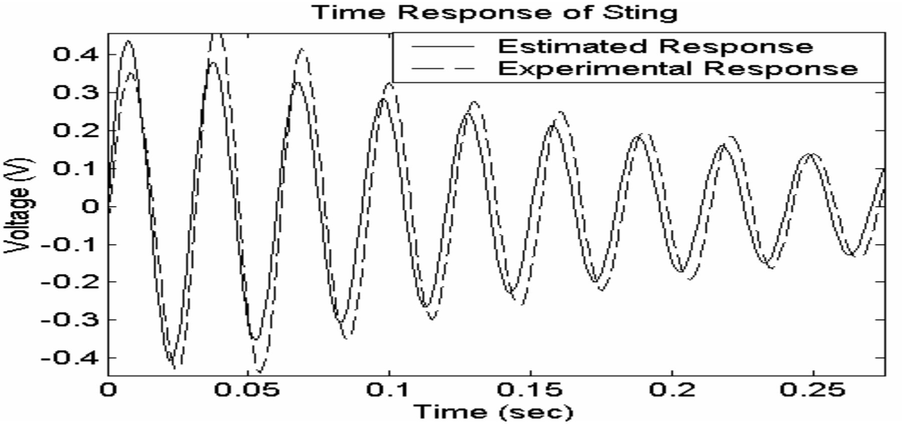

Figure 5. Comparison of estimated and experimental sting response

5. CONTROLLER IMPLEMENTATION

In order to carry out the real time implementation of the controller on the sting, based on impedance matching, the controller needs to be obtained from the estimated system transfer function of the sting[4]. The following steps have been implemented for the controller design.

1. The system transfer function (Y) is obtained from the Eigen Realization Algorithm (ERA). Let it be in the form of

$$Y = \frac{num(s)}{den(s)} \tag{3}$$

2. The zeros and poles of this system are obtained by taking the roots of numerator and denominator.
3. Critically damp the poles and zeros and bring it to the zero pole gain format.
4. The dereverberated transfer function is then obtained from these critically damped poles and zeros.

The controller transfer function obtained here is not proper because the numerator has a higher order than the denominator. So, the controller is divided into two controllers as shown below.

$$K_c = Z_d = \frac{(s + 210.4281)^2}{14.72s} = K_{c1}\ K_{c2} \tag{4}$$

K_c is broken down into K_{c1} and K_{c2} given by

$$K_{c1} = \frac{(s + 210.4281)}{14.72s} \text{ and } K_{c2} = (s + 210.4281) \tag{5}$$

Now, K_{c1} is a proper transfer function with equal orders of numerator and denominator. K_{c2} can be interpreted as a proportional and a derivative controller with the proportional gain = 210.4281 and derivative gain = 1. Implementation of K_{c2} can be made practical by replacing the derivative operator ‘s’ with a proper transfer function ‘s/(0.001s+1)’, which acts as a low pass filter with a cut-off frequency of 1000rad/sec. The Bode plots for the uncontrolled open loop response and controlled closed loop response of the sting are shown in Figure 6. A significant reduction in the magnitude of the controlled sting is observed in comparison to that of the uncontrolled sting. This shows that the impedance-based controller dampens the vibration of the sting.

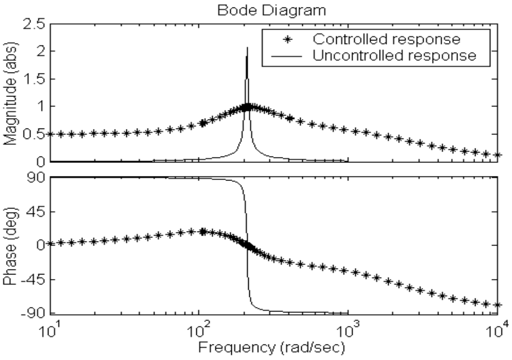

Figure 6. Bode Plot of the open and closed loop response

5.1 Closed Loop Response In Real-Time

After getting controlled response in the simulation, the real time implementation of Impedance control technique is carried out. An impulse signal (as shown in Figure 7) is given to the sting through DAC. The response of the sting is sensed using the strain gauge mounted on the aluminum block and acquired through ADC. The control action is initiated with a delay of 0.1 second to the impulse. The closed loop controlled response is shown in Figure 8.

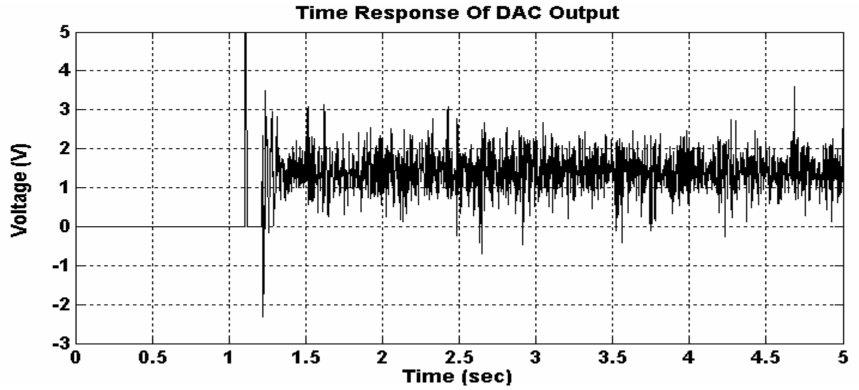

Figure 7. DAC (controller) output

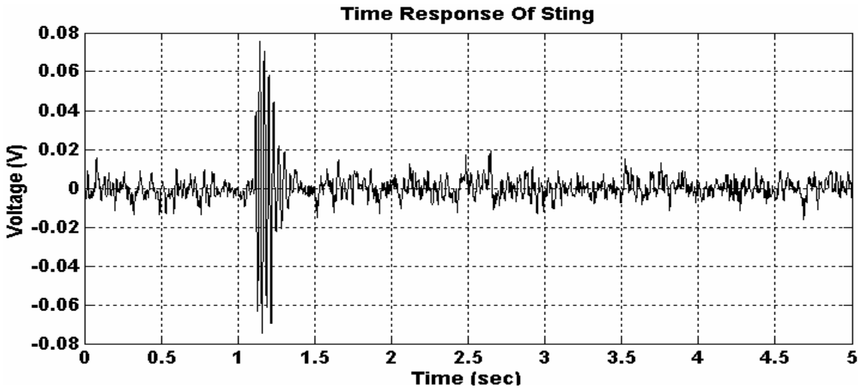

Figure 8. Controlled response

Closer view of the open and closed loop responses are shown in Figure 9 and Figure 10 respectively. From these figures it can be seen that for a given impulse in the open loop response the reasonable vibration reduction of the sting is reached after 1.2 seconds but in the closed loop response vibration reduction is achieved in about 0.2 seconds suggesting a significant reduction in vibration. This shows that the dynamic response of the sting can be effectively suppressed using impedance matching technique. The impedance matching technique can be efficiently employed in active vibration control, considering the simplicity involved in the computations and design of the impedance controller.

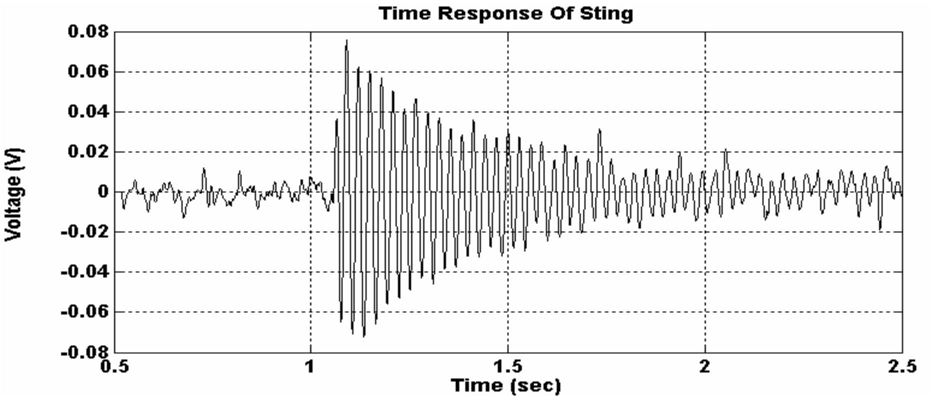

Figure 9. Closer view of open loop response of the sting

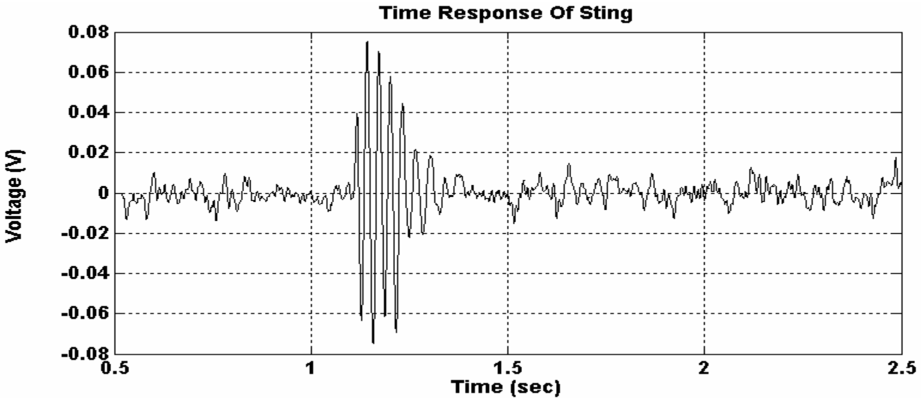

Figure 10. Closer view of closed loop response of the sting

6. CONCLUSIONS

The active vibration control of wind tunnel sting structures with piezoelectric stack actuators using an impedance matching control technique is studied in this paper. For this an idealized sting model structure was designed and fabricated, which was having the first natural frequency approximately equal to actual sting first mode natural frequency. Experiments were conducted to obtain collocated (actuator/sensor pair) open loop response and the transfer function of the wind tunnel sting model was estimated using ERA method.

From the system transfer function the controller is designed according to impedance matching theory. The real time closed loop experiments were conducted using dSPACE® DS1102 digital signal processor (DSP) card and MATLAB®. Experimental results demonstrate that significant vibration control/damping can be achieved with impedance matching control technique and piezo stack actuators. These experiments showed that it is feasible to generate sufficient energy in the sting model using the stack actuators. This technology will now be tested in the wind tunnel.

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REFERENCES

1. Crawley, E.F., and de Luis, J., "Use of Piezoceramic actuators as elements of intelligent structures," *AIAA Journal,* Vol. 25, No. 10, pp. 1373-1385, 1987.
2. Glaese, R.M., and Miller, D.W., "A generalized impedance matching feedback law for structural-acoustic control," Paper No. AIAA – 97 – 1209, 1997.
3. Kamath, G.M., Senthil Kumar, P. and Shivaprasad, M.V., "Vibration Control Studies Using an Impedance Method," *Proceedings of ISSS-SPIE* 2002.
4. Betros, R.S., Alvarez-Salazar, O.S., and Bronowicki, A.J., "Experiences with active damping and impedance matching compensators," *SPIE*, *Smart Structures and Intelligent Systems*, Vol. 1917, pp. 856 – 869, 1993.
5. Katsuhiko Ogata, *Solving Control Engineering Problems With MATLAB,* University of Minnesota, Prentice Hall, Englewood Cliffs, New Jersey 07632.
6. Juang, J., and Pappa, R.S., "An eigensystem realization algorithm for modal parameter identification and model reduction," *J.Guidance*, Vol 8, No. 5 pp.620-627, 1985.
7. *Applied System Identification*, Juang, J., Prentice Hall, Englewood Cliffs, New Jersey 07632, 1994.
8. Floating-Point Controller Board DS1102 User's Guide, Version 3.0, dSPACE GmbH, Germany, 1996.