ISSN 1 746-7233, England, UK
World Journal of Modelling and Simulation
Vol. 5 (2009) No. 2, pp. 113-119

Embedded output feedback controllers for piezoelectric actuated structures

L. R. Karl Marx[1]*, M. Umapathy[2], D. Ezhilarasi[2]

[1] Department of Electronics and Communication Engineering Thiagarajar College of Engineering, Maduari, 625013, India
[2] Department of Instrumentation and Control Engineering National Institute of Technology, Tiruchirappalli, 620015, India

(*Received October 11 2008, Accepted February 22 2009*)

Abstract. Microcontroller based fast output sampling feedback and periodic output feedback controllers are developed and tested for piezoelectric actuated structure. The use of microcontroller provides design flexibility, less component count and low cost solution.

Keywords: microcontroller, piezoelectric, output feedback

1 Introduction

Active control of large space structure is recognized as essential to the successful operation of structures as stable platforms for communications and observations. Recently, several active control systems have been successfully implemented to suppress the vibrations of simple structural elements. Applications of distributed piezoelectric sensors and actuators have been the subject of recent interest in the fields of smart structures, structural vibration control and acoustic noise isolation. Recent research has been focused on applications to vibration control and suppression[4, 6, 12].

Experimental studies using piezo-electric materials as sensor-actuator for controlling vibrations can be seen in [2, 3, 7]. Even though the experimental investigations on piezo-electric actuated structures are addressed in the literature, the focus on cost effective design of hardware and software aspects are not yet addressed. This paper proposes the implementation of fast output sampling and periodic output feedback control for structural vibration control using a common microcontroller Intel 8051. The proposed hardware and software design are modular in the sense that, the control algorithms can be applied to the embedded engineering systems.

2 Experimental setup

Experimental setup shown in Fig. 1 consists of a cantilever beam made up of aluminum; surface bonded with one pair of piezoceramic patches as sensor/actuator at a distance of $10mm$ from the fixed end. The piezoceramic bonded on the bottom surface acts as a sensor and one on the top surface acts as an actuator. To apply an excitation to the structure another piezoceramic patch is bonded on the top surface at a distance of 153 mm from the fixed end. The dimensions and properties of the beam and piezoelectric patches are given in Tab. 1 and Tab. 2.

The sensor output is given to the piezo sensing system which consists of a high quality charge to voltage converting signal conditioning amplifier. The conditioned piezo sensor signal is given as input to the sample and hold (LM 398) device. The output of the sample and hold device is given as the input of an 8 bit Analog

---

* Corresponding author. *E-mail address*: lrkarlmarx@tce.edu.

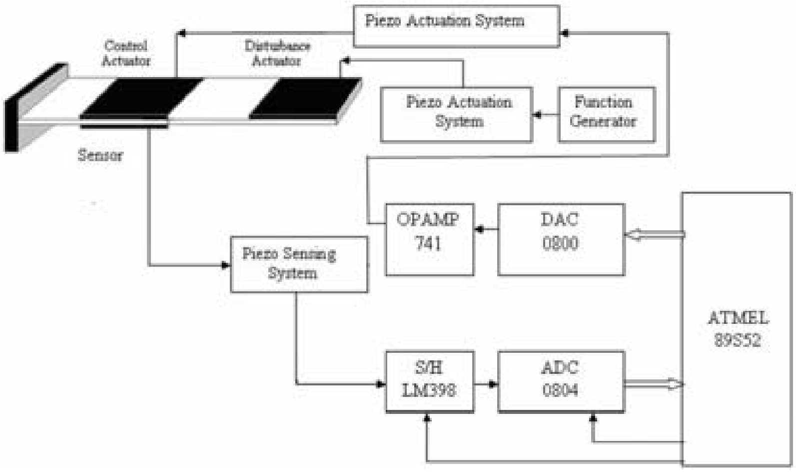


Fig. 1. Schematic diagram of experimental setup

to Digital Converter (ADC0804). The ADC output is fed to the port 1 of the ATMEL 89S52 microcontroller, where the control algorithm is fixed as a firmware in the EEPROM of 89S52. The control signal generated from the microcontroller is fed as an input to control actuator through a Digital to Analog Converter (DAC 0800) and piezo actuation system. The excitation signal to the disturbance actuator is applied using a function generator (Agilent 33220A) through a piezo actuation system.

Table 1. Properties and dimensions of the aluminium beam

Length (m)	l	0.3
Width (m)	b	0.0127
Thickness (m)	t_b	0.0023
Young's modulus (Gpa)	E_b	71
Density (kg/m^3)	ρ_b	2700
First natural frequency (Hz)	f	31.7

Table 2. Properties and dimensions of piezoceramic sensor/actuator

Length (m)	l_p	0.0765
Width (m)	b	0.0127
Width (m)	b	0.0127
Thickness (m)	t_a	0.005
Young's modulus (Gpa)	E_p	47.62
Density (kg/m^3)	ρ_p	7500
Piezoelectric strain constant (mV^{-1})	d_{31}	-247×10^{-12}
Piezoelectric stress constant (VmN^{-1})	g_{31}	-9×10^{-3}

The model of piezo actuated structure shown in Fig. 1 is obtained through recursive least square identification method[5]. The continuous state space model derived from the identified second order ARX model parameters is

$$\dot{x} = Ax + b\mathrm{u} + er; \ \mathrm{y} = c^T x \tag{1}$$

Where

$$A = \begin{bmatrix} -83.0583 & 218.2890 \\ -204.9014 & 76.7292 \end{bmatrix}, \quad b = \begin{bmatrix} -1.4349 \\ -1.708 \end{bmatrix}, \quad e = \begin{bmatrix} -0.2359 \\ -0.0477 \end{bmatrix}, \quad c^T = \begin{bmatrix} 1 & 0 \end{bmatrix}.$$

3 Controller design

3.1 Periodic output feedback controller design

The periodic output feedback controller[10, 11] is designed to reduce the amplitude of vibration of a cantilever beam at its first mode resonance. Let $(\Phi_\tau, \Gamma_\tau, c^T)$ and (Φ, Γ, c^T) be the discrete time invariant systems obtained by sampling the system in Eq. (1) at a rate $\frac{1}{\tau}$ and $\frac{1}{\Delta}$ respectively. Here sampling time $\tau = 10ms, \Delta = \frac{\tau}{N} = 2.5ms$, where N is equal or greater than the controllability index of (Φ_τ, Γ_τ). A stabilizing output injection gain G is designed for the system $(\Phi_\tau, \Gamma_\tau, c^T)$, such that the eigen values of $(\Phi_\tau + Gc^T)$ lie inside the unit circle. The output injection gain obtained is

$$G = [0.6318 \qquad 0.8677]$$

For the system $(\Phi_\tau, \Gamma_\tau, c^T)$ the control signal is generated according to

$$u(t) = K_l y(kt), \quad k\tau + l\Delta \le t < k\tau + (l+1)\Delta, \quad K_{l+N} = K_l, \quad \text{for} \quad l = 0, 1, \cdots N-1 \tag{2}$$

Where

$$K = \left[\ K_0 \quad K_1 \quad \ldots \quad K_{N-1}\ \right]^T$$

The periodic output feedback gain K obtained by solving $\Gamma_K = G$ with the performance index weight matrix R, P and Q is

$$K = \left[\ 36.1392 \quad 14.3302 \quad -3.5767 \quad -13.0638\ \right]^T$$

where

$$\Gamma = \left[\Phi^{\mathrm{N}-1}\Gamma \quad \Phi^{\mathrm{N}-2}\Gamma \quad \Phi^{\mathrm{N}-3}\Gamma \quad . \quad . \quad . \quad . \quad \Gamma\ \right]$$
$$R = [1]\,, Q = \begin{bmatrix} 2000 & 0 \\ 0 & 2000 \end{bmatrix}, P = \begin{bmatrix} 3000 & 0 \\ 0 & 3000 \end{bmatrix}.$$

3.2 Fast output sampling feedback controller design

A fast output sampling feedback controller[8, 9] is designed to reduce the amplitude of vibration of a cantilever beam at its first mode resonance. A stabilizing state feedback gain F is designed for the system $(\Phi_\tau, \Gamma_\tau, c^T)$, such that the eigen values of $(\Phi_\tau + \Gamma_\tau,\ F)$ are not at origin. The state feedback gain obtained is

$$F = [0.4216 \quad 20.6326]$$

The control signal $u(t)$ is then generated according to:

$$u(t) = \left[\ L_0 \quad L_1 \quad \ldots \quad L_{\ N-1}\right] \begin{bmatrix} y(k\tau - \tau) \\ y(k\tau - \tau + \Delta) \\ . \\ . \\ . \\ y(k\tau - \Delta) \end{bmatrix} \tag{3}$$
$$= Ly_k, \qquad k\tau < t \le (k+1)\tau$$

To realize the state feedback gain F by an output feedback gain L, the equation $LC = F$ is solved, where $C = (C_0 + D_0 F)(\Phi_\tau + \Gamma_\tau F)^{-1}$

$$C_0 = \begin{bmatrix} c^T \\ c^T\Phi \\ \cdot \\ \cdot \\ \cdot \\ c^T\Phi^{N-1} \end{bmatrix}, \qquad D_0 = \begin{bmatrix} 0 \\ c^T\Gamma \\ \cdot \\ \cdot \\ \cdot \\ c^T\sum_{j=0}^{N-2}\Phi^j\Gamma \end{bmatrix}.$$

The closed loop eigen values are the eigen values of the matrix in equation Eq. (4)

$$\begin{bmatrix} x_{k+1} \\ \Delta u_{k+1} \end{bmatrix} = \begin{bmatrix} (\Phi_\tau + \Gamma_\tau F) & \Gamma_\tau \\ 0 & LD_0 - FT_\tau \end{bmatrix} \begin{bmatrix} x_k \\ \Delta u_k \end{bmatrix} \tag{4}$$

and for the fast decay, the eigen values of $(LD_0 - FT_\tau)$ should be as close to the origin as possible. The gain matrix L may have elements with large magnitude. On implementation, this leads to the amplification of high frequency noise and causes the deterioration of plant performance. To determine the gain L with these constraints, an approximation $LC \approx F$ is solved instead of solving equation $LC = F$, but it can have considerable effect on the two problems described above. The LMI approach proposed in [9] is used to design L such that, the spectral norms of L and $(LD_0 - F\Gamma_\tau)$, as well as, the distance between LC and F can be controlled. Let ρ_1, ρ_2, ρ_3 represent upper bounds on the spectral norms of $L, (LD_0 - F\Gamma_\tau)$ and $(LC - F)$ respectively, and consider the system of LMIs:

$$\begin{gathered} \begin{bmatrix} -\rho_i^2 I & L \\ L^T & -I \end{bmatrix} < 0 \\ \begin{bmatrix} -\rho_2^2 I & (LD_0 - F\Gamma_\tau) \\ (LD_0 - F\Gamma_\tau)^T & -I \end{bmatrix} < 0 \\ \begin{bmatrix} -\rho_3^2 I & (LC - F) \\ (LC - F)^T & -I \end{bmatrix} < 0 \end{gathered} \tag{5}$$

Here, the three objectives have been expressed by upper bounds on matrix norms and each should be as small as possible. The value ρ_1 small means low noise sensitivity, ρ_2 small means fast decay of estimation error and ρ_3 small means that fast output sampling controller with gain L is a good approximation of the state feedback gain. The LMI in equation Eq. (5) are solved with $\rho_1 = 60, \rho_2 = 0.6, \rho_3 = 1$ by minimizing the linear objective under LMI constraints using the solver mincx ( ) in the LMI control tool box in MATLAB. The fast output feedback gain obtained as explained above is

$$L = [-12.2863 \quad -7.9771 \quad -1.6260 \quad 5.2543]$$

4 Implementation using microcontroller

4.1 Fast output sampling feedback controller

The experimental set up for piezo actuated structure with embedded controller is shown in Fig. 2. A sinusoidal excitation at first natural frequency with the amplitude of 10V peak to peak is applied to the disturbance actuator which makes the beam to vibrate at resonance. The piezoelectric sensor output is applied to a sample and hold circuit (S/H). The S/H circuit is designed with LM 398 and the microcontroller port 3.0 enables it for 7 microseconds as a sampling time, then the A/D conversion is initiated. During the conversion time, sampling is disabled and Hold signal is activated. This process continues for the successive samples.

The sampled analog signals are fed to the input of 8 bit ADC 0804, which is operating with a clock frequency of 606 kHz. The resistance and capacitance (RC) values are chosen as 10k and 150pf respectively. Use of poor tolerance components will shift the operating clock frequency. At the end of conversion (EOC) interrupt signal, the output of ADC is made available to microcontroller port 1 and it is disabled during the conversion time to avoid the error data interface. The ADC works with ±5 volts and has a resolution of 8 bits.

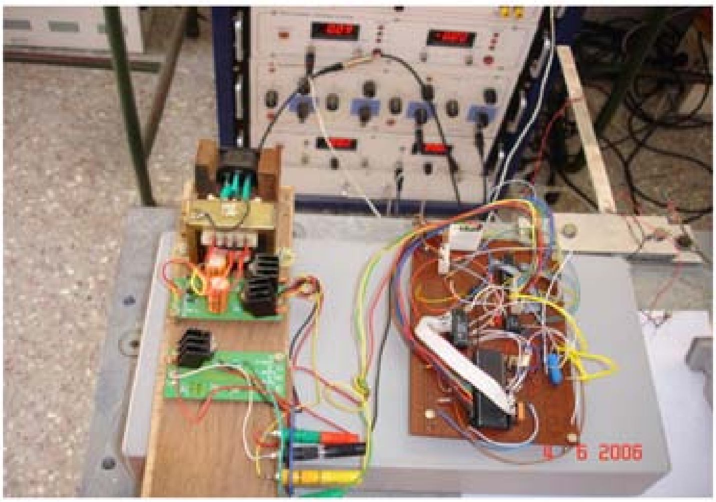
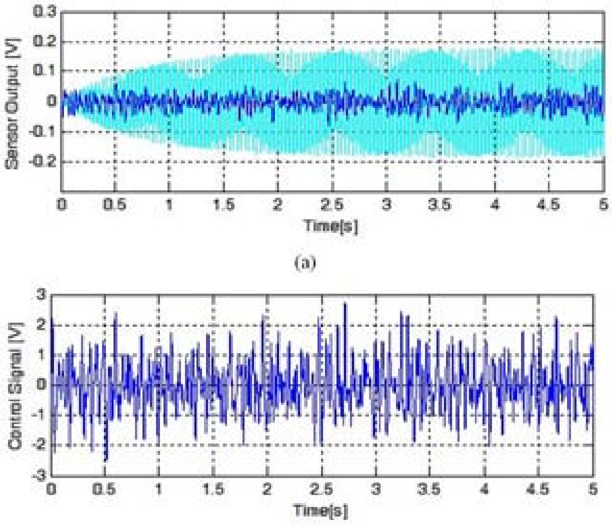


Fig. 2. Experimental set up with microcontroller interface

A firmware in hex code was developed and tested through 89S52 simulator[1], has been fused in to the EEPROM of the microcontroller. This firmware controls the overall function of the controller. The two timers, timer 0&1 of the 89S52 are initiated with $10(\tau)$ and $2.5(\Delta)$ millisecond durations respectively. At every Δ period the sensor output is interfaced to the A/D converter through S/H device. The converted sensor output at each Δ period is stored in RAM location of 89S52. In this case, the each interval consists of four Δ intervals. The stored values are multiplied with their respective controller gain as per the Eq. (3), a unique 8 bit controller output signal is computed and stored in RAM. Then the microcontroller waits and checks for the timer 0 to complete the τ duration. After the end of τ, the controller output is applied into the D/A converter through port 0 of 89S52. This process continues for the successive τ period.

The DAC 0800 gives an analog signal for an applied digital code from the microcontroller. Since the DAC provides a current output with phase inversion, an OP-AMP 741 is used to convert the current output into voltage with the phase compensation. The output of the OP-AMP is applied to the piezoelectric control actuator. The open loop response, closed loop response with fast output sampling feedback control and a control signal acquired from an embedded microcontroller is shown in Fig. 3.



(a)

(b)

Fig. 3. (a) Response to excitation: $\cdots\cdots$ uncontrolled; — controlled with Fast output feedback (b) Control signal.

The frequency response is captured using Digital storage oscilloscope (Agilent 33220A) and is shown in Fig. 4. The frequency response shows the vibration reduction of approximately 15 dB at first natural frequency.

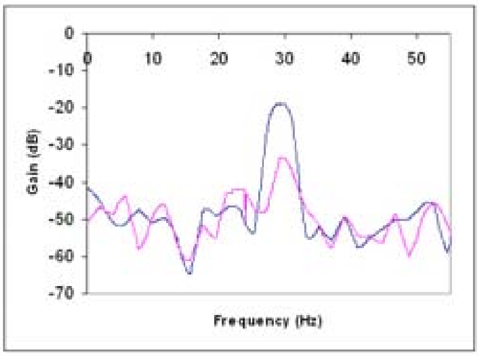


Fig. 4. Frequency Response: $\cdots\cdots$ Uncontrolled; — controlled

4.2 Periodic output feedback controller

The implementation of periodic output feedback control at every τ period the sensor output is interfaced to the A/D converter through S/H device. The converted sensor output at each period is stored in RAM location of 89S52. The stored value is multiplied with their respective controller gain as per the Eq. (2), a unique 8 bit controller output signal is computed for each Δ period and applied. This process continues for the successive τ period by updating the measurement at every τ. The open loop response, closed loop response with periodic output feedback control and a control signal acquired from an embedded microcontroller is shown in Fig. 5. The frequency response in Fig. 6 shows the vibration reduction of approximately 10 dB at first natural frequency.

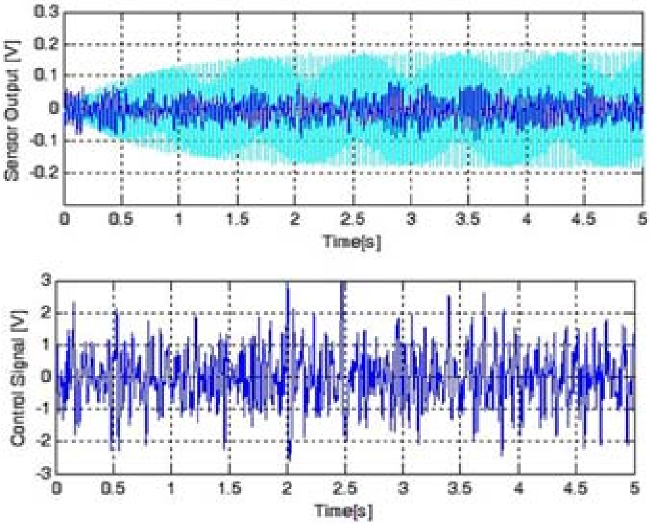


Fig. 5. (a) Response to excitation: $\cdots\cdots$ uncontrolled; — controlled with periodic output feedback (b) Control signal

5 Conclusion

Fast and periodic output sampling feedback controllers are designed for smart structure using embedded controller (Intel 8051). The experimental evaluation of the control algorithms is performed. The experimental

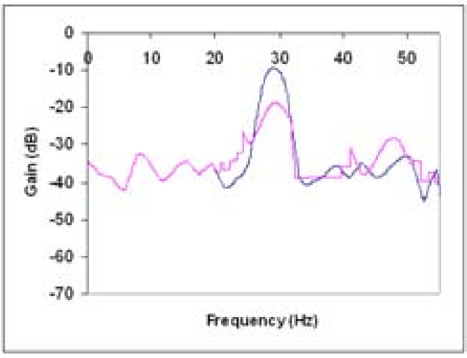


Fig. 6. Frequency Response: · · · · · · Uncontrolled; — controlled

results demonstrate the effectiveness of the controllers in suppressing the first vibration mode at resonance. The frequency response shows the vibration reduction of 15dB with fast output feedback control and 10dB with periodic output feedback control at their first natural frequency.

References

[1] Http://www.myke.com/umps.htm.

[2] A. Baz, S. Poh. Experimental implementation of the modified independent modal space control method. *Journal of sound and vibration*, 1990, **139**(1): 133–149.

[3] X. Bu, L. Ye, Z. Su. Active control of a flexible smart beam using a system identification technique based on armax. *Smart materials and Structures*, 2003, **12**: 845–850.

[4] I. Chopra. Review of state of art of smart structures and integrated systems. *AIAA Journal*, 2002, **40**(11): 2145–2187.

[5] D.Ezhilarasi, M.Umapathy, B.Bandyopadhyay. Design and experimental evaluation of piecewise output feedback control for structural vibration suppression. *Smart Materials and Structures*, 2006, **15**: 1927–1938.

[6] P. Pai, B. Wen, A. Naser. Structural vibration control using pzt patches and non-linear phenomena. *Journal of Sound and vibration*, 1998, **215**(2): 273–296.

[7] M. Umapathy, B. Bandopadhyay. Vibration control of flexible beam through smart structure concept using periodic output feedback. *System science*, 2000, **26**(1): 43–66.

[8] M. Umapathy, B. Bandyopadhyay. Design of fast output sampling feedback control for smart structure model. **in:** *SPIE*, vol. 4693, 2002, 222–233.

[9] H. Werner. Multimodel robust control by fast output sampling - an lmi approach. *Automatica*, 1998, **34**(12): 1625–1630.

[10] H. Werner, K. Furuta. Simultaneous stabilization based on output measurements. *Kybernetika*, 1995, **31**(4): 395–411.

[11] H. Werner, K. Furuta. Simultaneous stabilization by piecewise constant periodic output feedback. *Control Theory and Advanced Technology*, 1995, **10**(4): 1763–1775.

[12] S. Yang, C. Jeng. Structural vibration suppression by concurrent piezoelectric sensor and actuator. *Smart Materials and Structures*, 1996, **5**(6): 806–813.