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Sliding-mode Controller with Multisensor Data Fusion for Piezo-actuated Structure

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ABSTRACT

The benefits of multi-sensor data fusion (MSDF) in controlling the piezo-actuated beam structure using sliding-mode controller (SMC) have been brought out. The first two vibrating modes of the smart cantilever beam are measured by two sensors namely, piezoelectric sensor and laser displacement sensor. The states are estimated from the sensors outputs using information filter, which were then fused and applied as input to the controller. The controller has been designed from the linear dynamic model of a piezo-actuated beam, identified using linear recursive least square (RLS) method based on ARX model. A digital control system consisting of virtual instrumentation software LabVIEW, and USB data acquisition module NI 6008, was used for simulation and real-time control. Improved closed-loop performance was obtained when the controller design used fused data, as compared to the closed-loop performance obtained with a single sensor. The beam structure was a pilot model of the structures used in aerospace applications. Simulation and experimental results presented demonstrate the benefits of data fusion in controlling the vibration modes.

Keywords: Smart structure, information filter, data fusion, sliding mode controller, piezoelectric sensors, piezoceramics, multisensor data fusion

1. INTRODUCTION

Flexible structures are being used in many real-life systems, which include aircraft, bridges, buildings, etc. Originally, any structure can be regarded as flexible, since it experiences structural deformation even under small loading. In many situations, it is important to minimise these deformations as they may affect the stability and performance of the structures[1]. Smart materials, in particular, piezoceramics, are attractive for distributed actuation and sensing capabilities, because of their small size, low energy consumption, fast response, high efficiency, excellent sensing and significant actuation capabilities, and exhibit favourable bonding characteristics[2-3]. Hence, these are suitable for data fusion application. The use of piezoelectric sensors and actuators has shown promising applications in active vibration control of flexible structures[4-6]. System identification is an established modelling tool in engineering and numerous successful applications have been reported of this modeling tool[7]. Smart structures represent an interesting challenge for system identification methods and identification of piezo actuated cantilever beams[8-9].

Information filter, which is used as a state estimator, is computationally simpler. It is a more direct and a natural method of dealing with multisensor data fusion problems, and has a special advantage in decentralised sensor networks, because it provides a direct interpretation of node observation and contribution in terms of information. Applications of information filter and information fusion for large scale flexible space systems and target tracking can be seen[10-11]. Sensor data fusion is the process of combining outputs from sensors with information from other sensors, information processing blocks, databases or knowledge bases, into one representational form. This technique is expected to achieve improved accuracy and can lead to more specific inferences than what could be achieved by using a single sensor alone[12-14]. Multi-sensor data fusion (MSDF) for control and target tracking applications is presented[15-18].

Sliding-mode controller (SMC) is a powerful technique for the control of uncertain dynamic systems. The main advantages of SMC are its insensitivity to parameter variations and modelling errors, and rejection of external disturbances. In SMC, the system is allowed to vary its structure by properly and deliberately changing the sign and/or magnitude of the input, forcing discontinuities in the input wrt[19-22]. Application of SMC for aircraft, spacecraft, and vibration control of flexible structures is reported[23-28]. Multisensor data fusion for control of structural vibration of piezo actuated structures has not been reported in the literature. This has kindled the authors, to use the orchestra of above techniques, to control structural vibrations. The objective of this study is to show the benefits of data fusion for the control of structural vibration with SMC. Simulation and experimental investigations were carried out to demonstrate the performance of the controller.

2. EXPERIMENTAL SET-UP AND ITS MODEL

The experimental set-up shown in Fig. 1 comprises a flexible aluminium beam fixed at one end. Two piezoceramic patches were surface-bonded at a distance of 5 mm from the fixed end of the beam. The piezo patch bonded at the bottom

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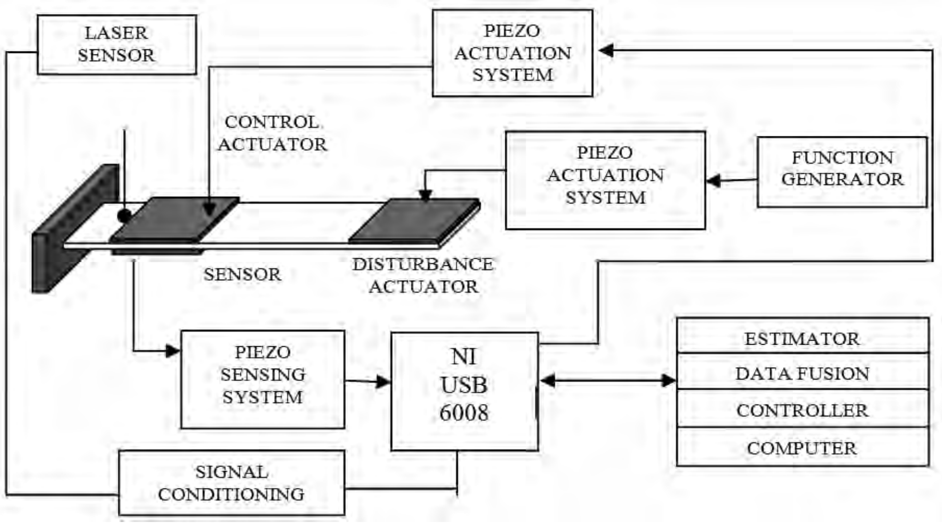

Figure 1. Schematic diagram of the experimental set-up.

surface was acting as sensor and the one on top surface was acting as an actuator. Excitation input was applied to the structure through another piezo patch, which was bonded on the top surface, at a distance of 370 mm from the fixed end. In addition, a non-contact type laser displacement sensor (Make: Acuity, Model: AR 200) was used as a second sensor. The properties and dimensions of the beam, piezoceramic patches, and the properties of laser displacement sensor are given in Tables 1 and 2 respectively. A piezoceramic of type SP-5H, which is equivalent to Navy Type VI, from M/s. Sparkler Ceramics Pvt. Ltd., India, was used. The laser sensor was 650 nm, Class II red visible diode and which was an accuracy of ± 0.2 per cent of span and had a resolution of 0.03 per cent of span.

Table 1. Properties and dimensions of the aluminium beam

Parameter	Symbol	Dimension
Length	l	0.40 m
Width	b	0.0135 m
Thickness	t_b	0.0001 m
Young’s modulus	E_b	71 GPa
Density	ρ_b	2700 kg m^{-3}
First natural frequency	f_1	5.04 Hz
Second natural frequency	f_2	32.84 Hz

Table 2. Properties and dimensions of the piezoceramic sensor/ actuator

Parameter	Symbol	Dimension
Length	l_p	0.0765 m
Width	b	0.0135 m
Thickness	t_a	0.0005 m
Young’s modulus	E_p	47.62 GPa
Density	ρ_p	7500 Kg m^{-3}
Piezoelectric strain constant	d_{31}	-247 x 10^{-12} m V^{-1}
Piezoelectric stress constant	g_{31}	-9 x 10^{-3} V m N^{-1}

The outputs of the piezo sensor and laser displacement sensor were conditioned and applied to the analog input channels of the data acquisition module NI USB-6008. The estimation, data fusion and control algorithm were developed using LabVIEW 8.5. The control signal generated was interfaced to a piezo actuation system, through the analog output of the data acquisition module NI USB-6008.

The dynamic model of the structure shown in Fig. 1, obtained using RLS method was based on the ARX model[9]. The state space model, derived from the identified fourth-order ARX model parameter is

$$\dot{x}(t) = Ax(t) + bu(t) + er(t) \qquad y(t) = Hx(t) \tag{1}$$

where

$$A = \begin{bmatrix} 76.9893 & 71.5731 & -45.5632 & 71.9048 \\ -136.1042 & 6.1271 & 116.6837 & -116.7537 \\ 115.7932 & -116.2021 & -6.5425 & 136.6781 \\ -70.8876 & 45.1268 & -71.2161 & -77.5364 \end{bmatrix}$$

$$b = \begin{bmatrix} 0.2046 \\ 0.1955 \\ -0.4427 \\ -0.0299 \end{bmatrix} \quad e = \begin{bmatrix} 0.0029 \\ 0.0265 \\ -0.0664 \\ 0.0588 \end{bmatrix} \quad H = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$$

3. IMPLEMENTATION OF INFORMATION FILTER AND MULTISENSOR DATA FUSION

3.1 Review of Information Filter

A brief review of information filter algorithm and data fusion algorithm is presented[10,15] as follows.

Consider a discrete system described by

$$x_d(k+1) = A_d x_d(k) + w(k) \tag{2}$$

where $x_d(k)$ are states of interest at time k, A_d the state transition matrix from time k to $k+1$, and $w(k)$ the associated process noise modelled as an uncorrelated white sequence with

$$E\,[w(i)w^T(j)] = \delta_{ij}\; Q(i) \tag{3}$$

where $Q(i)$ is process noise covariance matrix.

The system is observed according to the linear equation

$$z(k) = Hx_d(k) + v(k) \tag{4}$$

where $z(k)$ is the vector of observations made at time k, H the observation matrix and $v(k)$ the associated observation noise modelled as an uncorrelated white sequence with

$$E\,[v(i)v^T(j)] = \delta_{ij}\;R(i) \tag{5}$$

where $R(i)$ is measurement noise covariance matrix.

It is also assumed that

$$E[v(i)w^T(j)] = 0 \tag{6}$$

Information filter is essentially a Kalman filter expressed in terms of measures of information about the states of interest, rather than direct state estimates and their associated covariances. The two-key information-analytic variables are the information matrix (F) and information state vector $\hat{f}(i\,|\,j)$. The information matrix (F) is the inverse of the covariance matrix (P).

$$F(i\,|\,j) = P^{-1}(i\,|\,j) \tag{7}$$

The information state vector is the product of the inverse of the covariance matrix and the state estimate $\hat{x}(i\,|\,j)$ as

$$\hat{f}(i\,|\,j) = P^{-1}(i\,|\,j)\hat{x}(i\,|\,j) \tag{8}$$

The update equation for the information state vector is

$$\hat{f}(k\,|\,k) = \hat{f}(k\,|\,k-1) + H^T R^{-1}(k)z(k) \tag{9}$$

The expression for information matrix associated with the above estimate is

$$F(k\,|\,k) = F(k\,|\,k-1) + H^T R^{-1}(k)H \tag{10}$$

The information state contribution $i(k)$ from an observation $z(k)$, and its associated information matrix $I(k)$ are defined respectively as

$$i(k) = H^T R^{-1}(k)z(k) \tag{11}$$

$$I(k) = H^T R^{-1}(k)H \tag{12}$$

The information propagation coefficient $L(k\,|\,k-1)$, which is independent of the observation made, is given by the expression

$$L(k\,|\,k-1) = F(k\,|\,k-1)AF^{-1}(k-1\,|\,k-1) \tag{13}$$

Prediction

$$\hat{f}(k\,|\,k-1) = L(k\,|\,k-1)\hat{f}(k-1\,|\,k-1) \tag{14}$$

$$F(k\,|\,k-1) = \left[AF^{-1}(k-1\,|\,k-1)A^T + Q(k)\right]^{-1} \tag{15}$$

Estimation

$$\hat{f}(k\,|\,k) = \hat{f}(k\,|\,k-1) + i(k) \tag{16}$$

$$F(k\,|\,k) = F(k\,|\,k-1) + I(k) \tag{17}$$

3.2 Review of Multi-sensor Data Fusion

In the following, fusion of information terms $i(k)$ and $I(k)$ from sensor nodes to a common fusion centre is presented.

Consider a system containing N sensors, with a composite observation model given by Eqn. (4). The observation vector $z(k)$ is separated in to N sub-vectors of dimension N_i corresponding to the observation made by each individual sensor.

$$z(k) = [z_1^T(k), \ldots\ldots, z_N^T(k)]^T \tag{18}$$

Also, partition the observation matrix into sub-matrices was done corresponding to these observations

$$H = [H_1^T, \ldots\ldots, H_N^T]^T \tag{19}$$

The observation noise vector was also partitioned

$$v(k) = [v_1^T(k), \ldots\ldots, v_N^T(k)]^T \tag{20}$$

and it is assumed that these partitions are uncorrelated

$$E[v(k)v^T(k)] = R(k) = \text{blockdiag}\{R_1^T(k), \ldots\ldots, R_N^T(k)\} \tag{21}$$

so that the sensor model now consists of N equations in the form

$$z_i(k) = H_i x(k) + v_i(k) \tag{22}$$

with

$$E[v_p(i)v_q{}^T(j)] = \delta_{ij}\delta_{pq}R_p(i) \tag{23}$$

The information state contribution $i(k)$ from an observation $z(k)$, and its associated information matrix $I(k)$ are defined respectively as

$$i_j(k) = H_i^T R_i^{-1} z_i(k) \tag{24}$$

$$I_j(k) = H_i{}^T R_i{}^{-1} H_i \tag{25}$$

Comparing Eqn (11) and Eqn (22) implies

$$i(k) = \sum_{i=1}^{N} i_i(k) = \sum_{i=1}^{N} H_i^T R_i^{-1} z_i(k) \tag{26}$$

$$I(k) = \sum_{i=1}^{N} I_i(k) = \sum_{i=1}^{N} H_i{}^T R_i{}^{-1} H_i \tag{27}$$

so that

$$\hat{f}(k\,|\,k) = \hat{f}(k\,|\,k-1) + \sum_{i=1}^{N} i_i(k) \tag{28}$$

$$F(k\,|\,k) = F(k\,|\,k-1) + \sum_{i=1}^{N} I_i(k) \tag{29}$$

Each sensor incorporates a full state model and makes observations according to Eqn (22). They all calculate an information-state contribution from their observations in terms of $i_i(k)$ and $I_i(k)$, which are then communicated to the fusion centre and are incorporated into the global estimate through Eqns (28) and (29). The information state prediction is generated centrally using Eqns (14) and (15), and the state estimate itself may be found at any stage from

$$\hat{x}(i\,|\,j) = F^{-1}(i\,|\,j)\hat{f}(i\,|\,j) \tag{30}$$

3.3 Information Filter and Multi-sensor Data Fusion

The information filter and data fusion algorithms given in section 3.1 and 3.2 are developed, for the piezo actuated system given in Eqn (1), in LabVIEW 8.5.

4. DESIGN AND IMPLEMENTATION OF SLIDING MODE CONTROLLER

The SMC is designed to reduce the amplitude of vibration of first two modes of the piezo actuated beam. The controller utilises a high speed switching control law to drive the plant state trajectory on to a specified and user chosen switching surface and to maintain it on this surface for all subsequent time. A discrete time invariant linear system is obtained by sampling the system in Eqn (1) at a sampling interval of 0.01 sec, which is given as follows

$$x_d(k+1) = A_d x(k) + B_d u(k) + E_d r(k) \tag{32}$$

$$y_d(k) = Hx_d(k)$$

where

$$A_d = \begin{bmatrix} 0.9901 & 1 & 0 & 0 \\ -0.2781 & 0 & 1 & 0 \\ 0.9873 & 0 & 0 & 1 \\ -0.9904 & 0 & 0 & 0 \end{bmatrix} \qquad B_d = \begin{bmatrix} 0.0037 \\ -0.0021 \\ -0.0020 \\ -0.0005 \end{bmatrix}$$

$$E_d = \begin{bmatrix} 0.0002955 \\ -0.0003649 \\ -0.0000657 \\ 0.0003733 \end{bmatrix} \qquad H = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$$

The design for a desired sliding mode is a technique through which a linear switching function is determined.

$$S = Cx_d(k) \tag{33}$$

Consider a linear switching plane

$$S = C^T x_d(k) = 0 \tag{34}$$

The ideal quasi-sliding mode satisfies

$$S(k+1) = S(k) = 0; k = 0,1,2,..... \tag{35}$$

From Eqns (32) to (34),

$$C^T A_d x_d(k) + C^T B_d u(k) = S(k) = 0 \tag{36}$$

Solving for *u,* an equivalent control is given by

$$U_{eq} = \left[-(C^T B_d)^{-1} C^T A_d\right] x_d(k) \tag{37}$$

where $(C^T B_d)^{-1} \neq 0$ has been assumed, implying the controllability of the SMC system. Eqn (37) is linear in $x_d(k)$, so the dynamical equation of the ideal quasi-sliding mode is also linear, given by

$$x_d(k+1) = \left[A_d - B_d(C^T B_d)^{-1} C^T A_d\right] x_d(k)$$

$$C^T x_d(k) = 0 \tag{38}$$

The switching vector, which would make the system asymptotically stable, is obtained by using robust eigen value assignment. C^T is determined such that eigen values of $\left[A_d - B_d(C^T B_d)^{-1} C^T A_d\right]$ lie inside the unit circle. If the system matrix is represented in controllable canonical form, then switching coefficients can be determined using

$$C_1 = (-1)^{n-1} \lambda_1 \lambda_2 ..... \lambda_{n-1}$$

$$C_2 = (-1)^{n-2} (\lambda_2 \lambda_3 ... \lambda_{n-1} + \lambda_1 \lambda_3 ... \lambda_{n-1} + \lambda_1 \lambda_2 ... \lambda_{n-1}) \tag{39}$$

where *n* is the order of the system and $\lambda_1, \lambda_2, ... \lambda_{n-1}$ are the desired closed-loop eigen values.

The control function is chosen as

$$u_i(k) = -K_i x_d(k) \tag{40}$$

For the desired closed-loop eigen values of -0.7, -0.8 and -0.9, from Eqn (39)

C^T = [0.5040 1.9100 2.4000 1.0000]

From Eqn (37)

K_i = [-0.9904 1.4913 1.6319 3.3901]

4.1 Simulation Results

Simulations for without fusion and with fusion case are carried out using LabVIEW. The structure is initially excited at its first mode and later at its second mode natural frequency, to keep the beam at resonance. The open-loop, closed-loop and frequency responses for without fusion case are given in Fig. 2. For with fusion case, closed-loop and frequency responses are given in Fig. 3.

4.2 Experimental Investigation

The SMC designed in section 4 is implemented in real-time to control the structure shown in Fig 1. The sensor output are conditioned and sampled at every 0.01 sec, and digitised by the ADC present in NI USB 6008 module. The digital control signal generated by the controller is updated for every 0.01 sec and applied to the control actuator using the DAC of NI USB 6008 module. To asses the performance of the designed controller, the structure is at first mode resonance and later at second mode resonance. The excitation signal is sinusoidal having an amplitude of 20 V_{PP}. The open-loop response in time and frequency domain is given in Fig 4. The closed-loop response in time and frequency domain for without fusion and with fusion cases are given in Figs 5 and 6.

4.3 Results and Discussion

The amplitude of vibration suppression for first mode and second mode resonance, obtained in case of without fusion and with fusion are given in Table 4. It is observed from the simulation and experimental results that higher vibration reduction is obtained in case with fusion.

5. CONCLUSIONS

The design and experimental evaluation of SMC for vibration suppression of a piezo actuated beam with data fusion has been presented. The performance of the controller in case of without fusion and with fusion is investigated. The simulation and experimental results, shows that closed-loop response which uses fused data gives improved reduction in amplitude of vibration. This work uses information filtering, information fusion and sliding mode controller, can be extended to the real world problem of controlling a large flexible aerospace structure. The necessary electronics required for that implementation can be provided by hardware and software used in this work, so that will be applied in aerospace avionics.

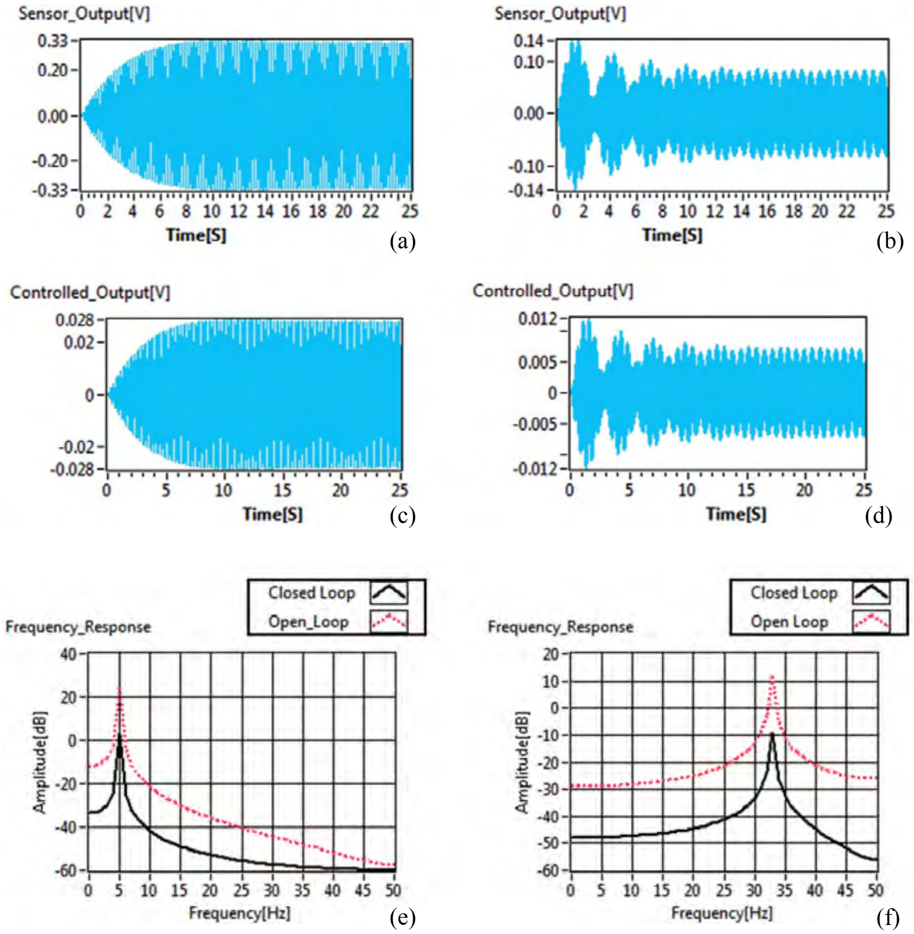

Figure 2. Open-loop responses when the beam is excited: (a) at first mode, (b) at second mode; Closed-loop response when the beam is excited without fusion, (c) at first mode, (d) at second mode; Open and closed-loop frequency response when the beam is excited without fusion, (e) at first mode, and (f) at second mode.

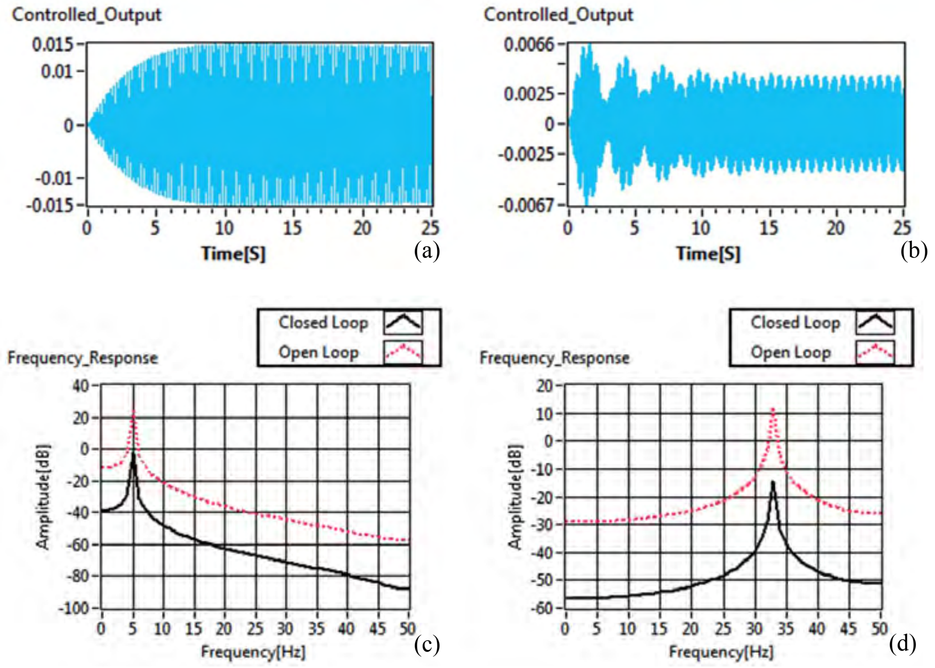

Figure 3. Closed-loop responses when the beam is excited with fusion: (a) at first mode, (b) at second mode; Closed-loop response when the beam is excited with fusion, (c) at first mode, (d) at second mode; open and closed-loop frequency response when the beam in excited with fusion.

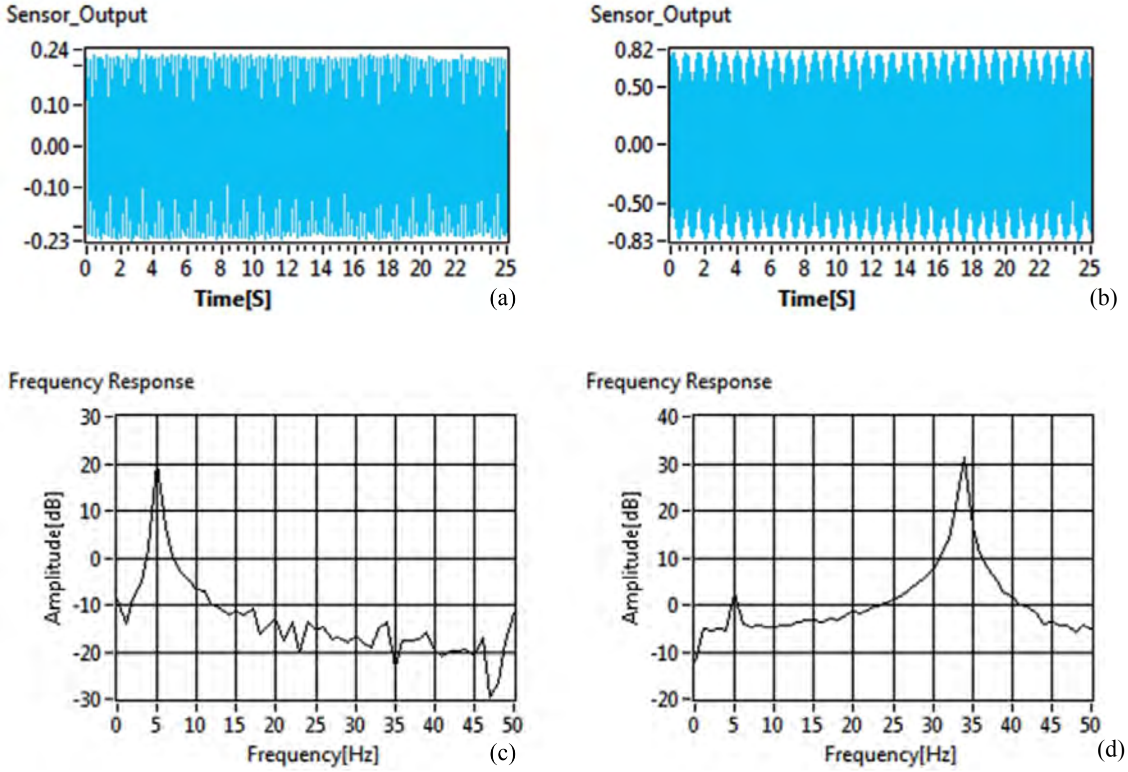

Figure 4. **(a) Open-loop responses when the beam is excited at first mode, (b) open-loop responses when the beam is excited at second mode, (c) open-loop frequency responses when the beam is excited at first mode, and (d) Open-loop frequency response when the beam is excited at second mode.**

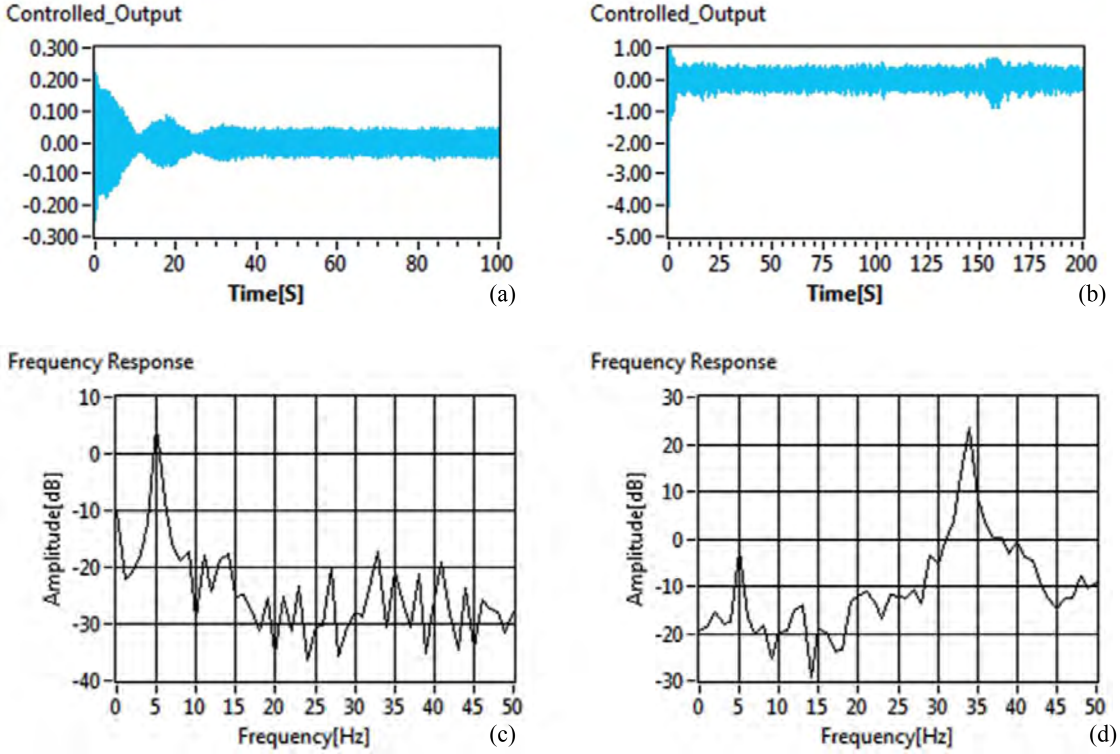

Figure 5. **(a) Closed-loop responses when the beam is excited at first mode (without fusion), (b) Closed-loop response when the beam in excited at second mode (without fusion), (c) Closed-loop frequency response when the beam is excited at first mode (without fusion), and (d) Closed-loop frequency responses when the beam in excited at second mode (without fusion).**

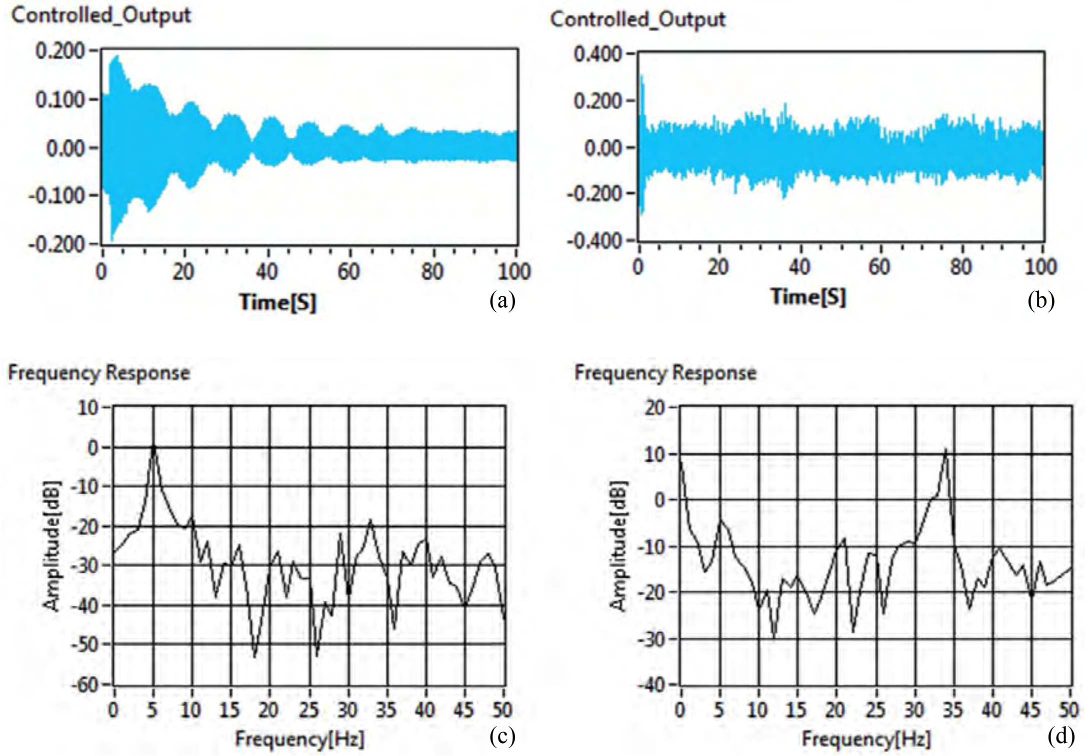

Figure 6. (a) Closed-loop response when the beam in excited at first mode (with fusion), (b) Closed-loop response when the beam in excited at second mode (with fusion), (c) Closed-loop frequency response when the beam in excited at first mode (with fusion), and (d) Closed-loop frequency response when the beam in excited at second mode (with fusion).

Table 4. Comparison of simulation and experimental results

	Simulation		**Experimental**	
	First mode	**Second mode**	**First mode**	**Second mode**
Open-loop	22 dB	11 dB	19 dB	32 dB
Closed-loop without data fusion	2 dB	-10 dB	3 dB	23 dB
Closed-loop with data fusion	-1 dB	-12 dB	0 dB	11 dB

REFERENCES

1. Chopra, I. Review of state-of-the-art of smart structures and integrated systems. *AIAA Journal*, 2002, **40**, 2145-87.
2. Sun, D.; Wang, D. & Xu, Z. L., Distributed piezoelectric segment method for vibration control of smart beams, *AIAA Journal*, 1996, **35**(3), 583-84.
3. He, C. & Jha, R. Experimental evaluation of augmented UD identification based vibration control of smart structures. *J. Sound Vib*., 2003, **274**, 1065-078.
4. Hanagud, S.; Obal, M.W. & Callise, A.J. Optimal vibration control by the use of piezoceramic sensors and actuators. *J. Guid. Cont. Dyn*., 1992, **15**(5), 1199-206.
5. Choi, Seung Bok; Cheong, Chae Cheon & Lee, Chul Hee. Position tracking control of a smart flexible structure featuring a piezofilm actuator. *J. Guid. Cont. Dyn.*, 2006, **19**(6), 1364-69.
6. Yang, S.M. & Lee, Y.J. Vibration suppression with optimal sensor/actuator location and feedback gain. *Smart. Mater. Struct*., 1993, **2**, 232-9.
7. Ljung, L. System identification theory for the user. Prentice Hall, Englewood Cliffs, NJ, 1999.
8. Bu, X.; Ye, L.; Su, Z. & Wang, C. Active control of a flexible smart beam using a system identification technique based on ARMAX. *Smart Mater. Struct*., 2003, **12**, 845-50.
9. Ezhilarasi, D.; Umapathy, M. & Bandyopadhyay; B. Design and experimental evaluation of piecewise output feedback control for structural vibration suppression, *Smart Mater. Struct*., 2006, **15**, 1927-938.
10. Mallory, Gregory J.W. & Miller, David W. Decentralised state estimation for flexible space structures. *J. Guid.*

Cont. Dyn., 2000, **23**(4), 665-72.

11. Raol, J.R. & Girija. G. Sensor data fusion algorithms using square-root information filtering. *IEE Proceedings on Radar Sonar and Navigation*, 2002, **149**(2), 89-96.
12. Mutambara. Arthur G.O. Decentralised estimation and control for multisensor systems. CRC Press Inc., USA, 1998. 1-17.
13. Hall, David L. Mathematical techniques in multisensor data fusion. Artech House Inc., Norwood, MA, 1992.
14. Girija, G. & Raol, J. Application of information filter for sensor data fusion. *In* Proceedings of 38th Aerospace Sciences Meeting & Exhibit, Reno, NV, 2000, pp. 1-10.
15. Grime, S. & Durrant, Whyte. H.F. Data fusion in decentralised sensor networks. *Control Eng. Practice*, 1994, **2**(5), 849-63.
16. Pao, Lucy. Y. Measurement reconstruction approach for distributed multisensor fusion. *J Guid. Control Dyn.*, 1996, **19** (4), 842-47.
17. Beugnon, C.; Singh, T.; Linas, J. & Saha, Rajat K. Adaptive track fusion in a multisensor environment. *In* Proceedings of International Conference on Information Fusion, Parc de la villette, Paris, 2000, TuC2-24-TuC2-31.
18. Roecker, J.A. & McGillem, C.D. Comparison of two-sensor tracking methods based on state vector fusion and measurement fusion. *IEEE Trans. Aerosp. Electron. Syst*., 1988, **24**(4), 447-49.
19. Utkin, V.I. Variable structure systems with sliding mode. *IEEE Trans. Automat. Control*, 1977, **22**(2), 212-22.
20. Decarlo, K.A.; Zak, S.H. & Mathews, G.P. Variable structure control of nonlinear multivariable systems: A tutorial. *Proceedings of the IEEE*, 1988, **76**(3), 212-32.
21. Young, K.D.; Utkin, V.I. & Ozguner, U. A control engineer's guide to sliding mode control. *IEEE Trans. Control Syst. Technol.*, 1999, **7**, 328-42.
22. Zinober, A.S.I. Deterministic control of uncertain systems. Peter Peregrinus Ltd., London, 1990, pp. 2-3.
23. Wang, Der An & Huang, Yeii Mei. Application of discrete time variable structure control in the vibration reduction of a flexible structure. *J. Sound Vib*., 2003, **261**, 483-501.
24. Hu, Qinglei & Ma, Guangfu. Variable structure control and active vibration suppression of flexible spacecraft during attitude maneuver. *J. Aerospace Sci. Technol.*, 2005, **9**, 307-17.
25. Bandyopadhyay, B.; Kurode, Shailaja & Gandhi, P.S. Sliding mode control for slosh-free motion – A class of underactuated system. *J. Advanced Mechatronic Syst.*, 2009, **3**, 203-13.
26. Deng, Mingcong; Inoue, Akira & Baba, Yusuke. Operator based non-linear vibration control system design of a flexible arm with piezoelectric actuator. *J. Advanced Mechatronic Syst.*, 2008, **1**, 71- 76.
27. Hung, John Y.; Gao, Weibing & Hung, James C. Variable structure control: A survey. *IEEE Trans. Ind. Electron*, 1993, **40**(1), 2-20.
28. Allen, Mathew; Zazzera, Franco Bernelli & Scattolini, Riccardo. Sliding mode control of a large flexible space structure. *Control Engineering Practice*, 2000, **8**, 861-71.

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