Active Vibration Control of Composite Beam Using a Strain Gages Sensor and Piezoelectric Patch Actuator

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ABSTRACT

This article investigates active vibration suppression of a flexible beam with a low dominant frequency using strain gages sensor and dual layer piezoelectric actuators. The strain gages sensor and piezoelectric actuators are in patch form and are surface-bonded to the cantilevered end of the composite beam. The feedback PID control algorithm is adopted for active vibration control of the composite beam. The effects of different gains in proportional, integral and derivative control are considered experimentally. Experiments are conducted to verify the effectiveness of the vibration suppression and to compare the damping effect with different adjustment of PID gains. With given experimental results are determined the best effectiveness of active structure.

Introduction

Recent studies of structural control systems using piezoelectric actuators have become a routine in order to increase the effectiveness in vibration suppression of structures [1,2]. Integration of actuators and sensors on the structure area has changed its modal parameters. The selection and optimization of sizing and location of actuators and sensors for active vibration control of flexible structures has proved to be one of the most important issues in the designing of active structures since these parameters have a major influence on the control system performance [3].

An active structure consists of a host structure incorporated with sensors and actuators coordinated by a controller. The integrated structure includes some vibration modes of the structure whose dynamic response must be considered. If the set of actuators and sensors is located at discrete points of the structure, they can be treated separately [4]. With the developments of sensor/actuator technologies many researchers have concentrated on active vibration control using different types sensors and actuators [5,6].

Vibration control is one of the major issues that need to be considered carefully in designing a structural system exposed to external disturbances. Depending on sensors, the vibrations can be controlled by different control strategies. However, the acquaintance with system parameters and all state variables are required of controller development. Reviewing available articles related to the active vibration control of smart structures leads to the conclusion that, to the best of our knowledge, no study has been reported on the detailed experimental analysis of a PID controller used for active vibration suppression of smart structures.

This paper presents an experimental investigation of the active vibration control of a smart cantilever beam using strain gages and piezoelectric actuator with the PID control strategies. The appropriate adjustment of proportional, integral and differential gains is determined with effectiveness of active control system to damp the free vibration of composite beam.

Active vibration control system

Active structure is the result of the integration of the behavior of the structural subsystem with that of the controller, the actuators, and the sensors; the only reasonable approach to design this is to design the system as a whole [7]. Active structure consists of next elements: composite cantilever beam, strain gages and PZT actuator (figure 1).

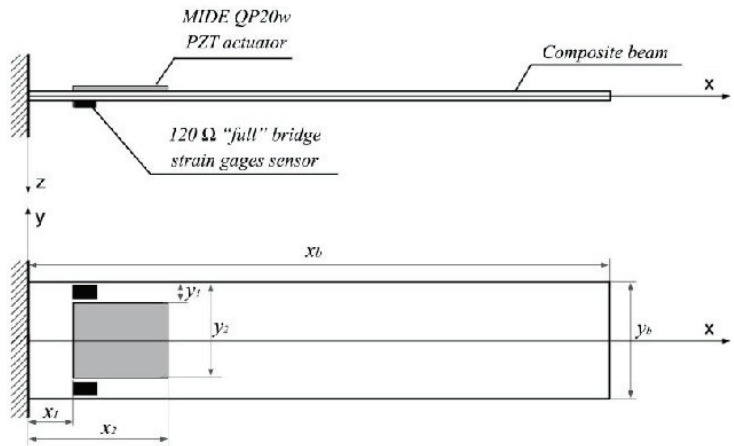

Figure 1. The cantilever beam with piezoelectric atuator and strain gages sensor

The length of the beam is 300mm, and its width is 60mm. Total thickness is 1.1 mm. The beam is made of 5 symmetric layers whose orientation is (0°/45°/-45°/45°/0)s. The tip and bottom layers, whose orinentations are 0°, are made of graphit-epoxy T300J, and other layers are made of uni-directional grafit-epoxy K63712 (12K). The piezoelectric dual layer PZT actuator, QP20w, produced by "Mide", is mounted near the fixed end at x_1=25 mm. For measuring displacements, the strain gages sensor (120 Ω Wheatstone full bridge), where two strain gages are placed at the same longitude position on both sides of actuator and other two at opposite side of beam. Position of actuator and sensor platform are determined on fuzzy optimization approach based on the pseudogoal function for multi-objective problem. [3]

The controller and high voltage amplifier are added to active structure and the active vibration system (ACV) is configured. The controller is developed on microcontroller platform PIC32MX440F256H, which acquires the output signal y(t) from the strain gages sensor, determines the control signal u(t) on feedback PID control low and across the high-voltage amplifier delivers to actuator. The system sampling frequency is set to 1 kHz. The controllability and observability of the system are two fundamental qualitative properties of dynamic systems. These characteristics are in relation with gains in proportional, integral and derivative control. The effects of different gains in proportional, integral and derivative control are considered experimentally.

Experimental set-up

The experimental setup for the vibration damping identification is illustrated in figure 2.

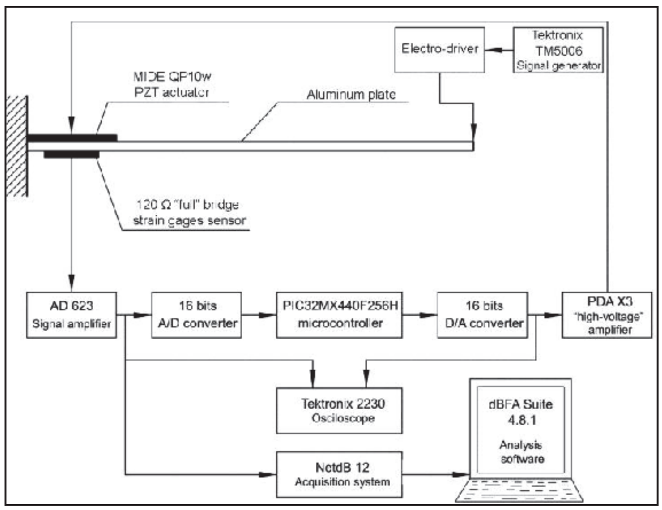

Figure 2. Experimental setup for determination of PID gains in system of ACV

The initial PID are obtained by using the Ziegler-Nichols method. The critical gain, K_{cr} and period, P_{cr} are defined as the amplifier ratio at which response of the controlled plant has sustained oscillations and closed-loop system is at the stability limit. The proportional, integral and derivative gains of the PID controller obtained with obtained with Ziegler-Nichols method are $K_p = 2.6$, $K_i = 0.03$ and $K_d = 50$. In order to investigate how different values of the gains affect the control performances (damping time in closed loop) of the active composite beam, an experiment was performed for several combinations of these gains with aim to find the optimal combination of PID gains.

Experimental results

Based on modal analysis approach [8] and the modeling of piezoelectric actuators [9], applying the Laplace transformation, the dynamical model of active composite beam without control under static initial conditions is defined. The active composite beam is loaded by the force at the tip, and thus the static deflection of the tip equals 30 mm [5]. Vibrations occur when the force is suddenly removed. Time and frequency response of active composite beam for free vibration under static initial conditions are given in figure 3.

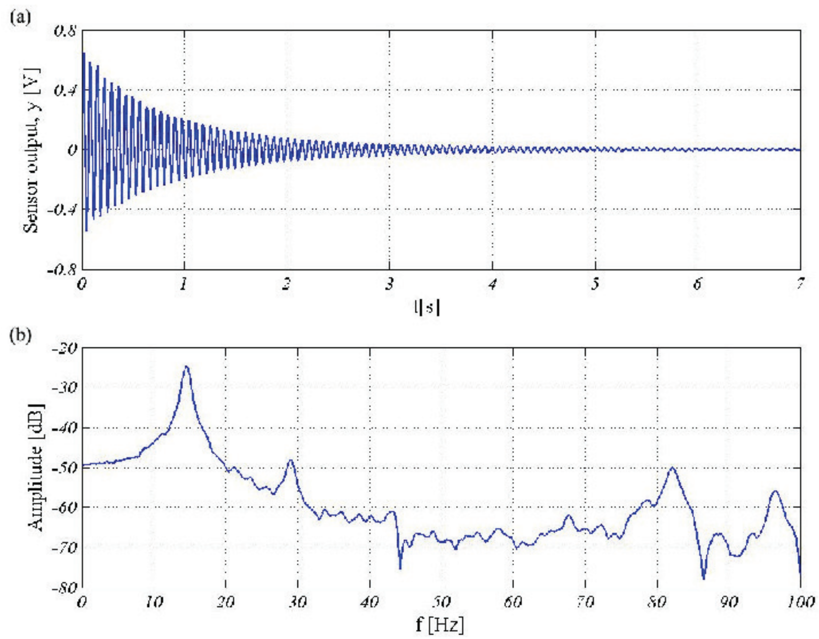

Figure 3. Active composite beam without control under static initial condition: (a) time response, and (b) frequency response

The free vibrations of active composite beam in open loop are cancelled after 7 seconds. With experimental FRFs (open loop) the dynamical characteristics of active composite beam are determined.

To determine the optimal factors combination, totally 25 different combinations of K_p, K_i and K_d were tested in the experiment. First, the proportional gain was adjusted, integral and differential gains were set to values determinate from Ziegler-Nichols method. The time damping for 3 proportional gains is given in figure 4.

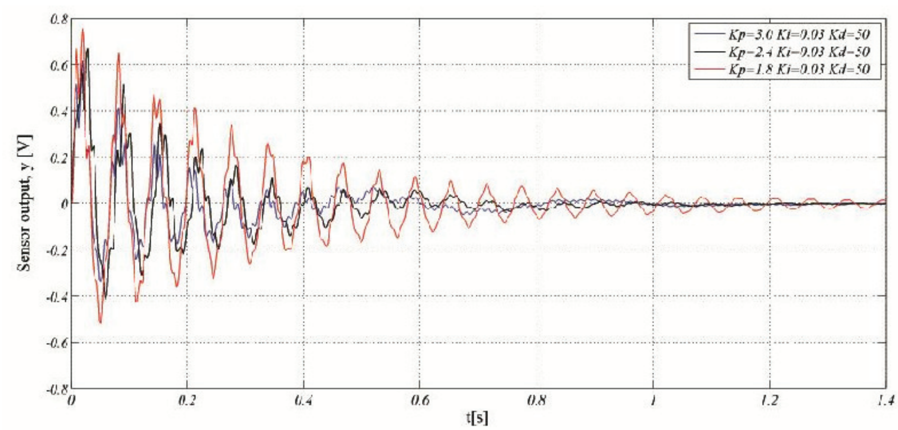

Figure 4. Time response of active composite beam in closed loop for different proportional factors

In table 1 is given the damping time and damping ratio for each proportional gain.

Table 1. Damping time for different proportional gain

Gains of PID controller			Damping time [s]	Damping ratio, ζ	
Kp	*Ki*	*Kd*		ζ_{pos}	ζ_{neg}
	open loop		7.36	0.01349	0.01353
3.0	0.030	50	1.21	0.07510	0.03782
2.6	0.030	50	1.25	0.05642	0.03452
2.4	0.030	50	1.28	0.05064	0.03298
2.2	0.030	50	1.42	0.04920	0.02898
2.0	0.030	50	1.73	0.04702	0.02565
1.8	0.030	50	2.15	0.04026	0.02289
1.6	0.030	50	2.53	0.02796	0.02271

It can be seen from table 1 that the best control performances are shown by the PID controller with the following factors Kp=3.0, Ki=0.03 and Kd=50, but this factor is not chosen for next consideration. The control performance is evaluated in terms of their ability to reduce the relative displacement at sub harmonic field of first mode at 2.4 Hz. The proportional gain is chosen as Kp=2.4.

The next set of experiments were contained the change of integral factors. The eleven tests with different integral factors are conducted: Ki=0.02, 0.025, 0.03, 0.035, 0.04, 0.045, 0.05, 0.055, 0.06, 0.07 and 0.08. After analysis of tests with different integral factors it can be concluded that the increase of integral factor above 0.05 increase the instability of system at sub harmonic frequency of 2.4 Hz. The attenuation of signal with integral factor is dominant for values higher then given integral factor from Ziegler-Nichols method. The damping time for values from Ki=0.02 to Ki=0.05 is very close each other, but the attenuation of the sensor signal in start of free oscillation is higher for factors Ki=0.035 to Ki=0.05. In according with this facts the Ki=0.035 is chosen for integral factor in PID controller.

The next set of experiments was conducted with aim to choose the optimal differential factor for PID controller. The seven different factors are analyzed, the time damping of four different factors is shown in figure 5.

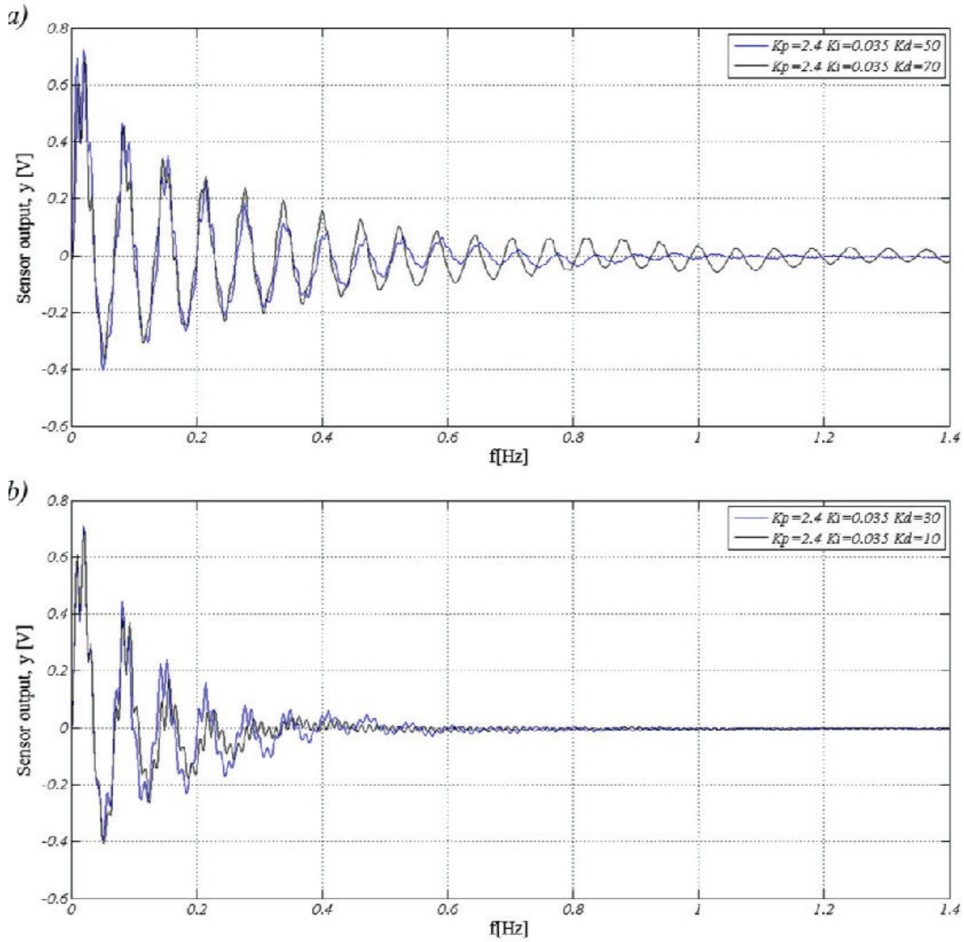

Figure 5. Time response of active composite beam in closed loop for different differential factors: a) Kd=50 and Kd=70, b) Kd=30 and Kd=10

In table 3 is given the damping time and damping ratio for each derivative gain. It can be seen from table 1 that the best control performances are shown by the PID controller with the following factors Kp=2.4, Ki=0.035 and Kd=10.

Table 3. Damping time for different derivative gain

Gains of PID controller			Damping time [s]	Damping ratio, ζ	
Kp	*Ki*	*Kd*		ζ_{pos}	ζ_{neg}
	open loop		7.36	0.01349	0.01353
2.4	0.035	70	2.42	0.02955	0.02419
2.4	0.035	60	1.82	0.03691	0.03171
2.4	0.035	50	1.31	0.04987	0.03312
2.4	0.035	40	1.22	0.05277	0.04026
2.4	0.035	30	1.17	0.07668	0.06564
2.4	0.035	20	1.08	0.08027	0.09232
2.4	0.035	10	0.95	0.08890	0.11007

Conclusion

The Ziegler-Nichols tuning method is an appropriate method, but manual corrections for PID factors are preferable for maximal vibration suppression. With good manual corrections the damping time can be reduced for more than 20 %. The number of full oscillation is reduced for more than 5 cycles. Those corrections must be carefully tuning without any perturbation of stability margin.
Developed AVC system is

References

[1] Yang M., Lee J. Y. (1993) Optimization of non-collocated sensor/actuator location and feedback gain in control systems, Journal of Smart Materials and Structures, 2, pp. 96-102.

[2] Fuller R. C., Elliott J. S. and Nelson A. P. (1996) Active Control of Vibration, Academic Press, New York.

[3] Zorić, D.N., Simonović, M.A., Mitrović, S.Z. and Stupar, N.S. (2012) Multi-Objective Fuzzy Optimization of Sizing and Location of Piezoelectric Actuators and Sensors, FME Transactions, 40 (1), pp. 1-9.

[4] A. Preumont, 2002, Vibration Control of Active Structures, 2nd Ed., Kluwer Academic, Dordrecht

[5] Jovanović M. M, Simonović M.A., Zorić, D.N., Lukić S.N, Stupar N.S and Ilić S.S. (2013) Experimental studies on active vibration control of a smart composite beam using a PID controller, Smart materials and structures, 22 (11)

[6] Kwak MK and Heo S (2007) Active vibration control of smart grid structure by multiinput and multioutput positive position feedback controller, Journal of Sound and Vibration 304(1-2), pp. 230–245.

[7] Alkhatib R. and Golnaraghi M. F. (2003) Active Structural Vibration Control: A Review, The Shock and Vibration Digest, 35 (5), pp. 367-383.

[8] Meirovitch L. (1986) Elements of Vibration Analysis,, 2nd edn, Sydney:McGraw–Hill,

[9] Moheimani S. and Fleming A. (2006) Piezoelectric Transducers for Vibration Control and Damping ,London: Springer