Effectiveness of active vibration control on smart plate using a PID controller

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ABSTRACT
This paper presents design, development and experimental verification of the active vibration control system of aluminum plate. The active structure consists of an aluminum rectangular plate as the host structure, strain gages as the sensor element and piezoceramic patch as the actuation element. Based on characteristics of the integrated elements, the completely active vibration control system is designed and developed. The active vibration control system is controlled on PID control strategy. Control algorithm was implemented on the PIC32MX440F256H microcontroller platform. The experiment considers active damping control under periodic excitation. Experiments are conducted to verify the effectiveness of the vibration suppression and to compare the damping effect with different adjustment of PID gains. Experimental results corresponding to the developed active vibration control system are presented and affirmed effectiveness of vibration active damping on proposed active structure.

Introduction

The presence of vibrations is a common problem in mechanical structures, particularly in flexible parts, for space industry, where large, lightly damped, flexible structures characterized by closely spaced modes and low natural frequencies are common. This can be reduced by making such parts strong or heavy enough. For many applications, e.g. in aircrafts and spacecrafts, it is desirable to keep the weight as low as possible, which makes such solutions less suitable. In order to improve the performances of light structure, the best solution is the system of active vibration control. In the case when such a system is embedded in the structure it is often referred to as an active structure.

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 are located at discrete points of the structure, they can be treated separately. [1]

Reviewing available articles regarded to the active vibration control of flexible structures it can be concluded that, to the best of our knowledge, no study has been reported on the detail active structures development process with PID controller, strain gages like a sensor and PZT material for actuation. [2,3,4]

In this paper the development process of the active vibration control system is presented. The sensor is 120 Ω Wheatstone "full bridge" (strain gages) platform. The actuator is one layer PZT fiber reinforced actuator. Optimization of orientation of piezoelectric actuator on the clamp-free-free-free (CFFF) aluminum plate was performed by using the fuzzy optimization strategy [5]. Control PID algorithm is implemented on "PIC32-PINGUINO-OTG" board, with integrated PIC32MX440F256H microcontroller. The vibration suppression efficiency of the developed system was verified experimentally on active plate with periodic excitation at eccentricity pulley.

Design of active structure

In this section, the elements and their incorporation on structure (aluminum plate) for active vibration control application are presented. The cantilever aluminum plate (280 x 200 x 1 mm) is considered.

The Wheatstone bridge is usually used to measure the deformation of mechanical system. The four arms of the bridge circuit are formed by the resistances R1 to R4 (Fig. 1(a)). The integrated sensor platform is given on Fig. 1(b).

The corner points 2 and 3 of the bridge, designate the connections for the bridge excitation voltage (V_S); the bridge output voltage (V_0), is available on the corner points 1 and 4. The output voltage is proportional to plate deformation.

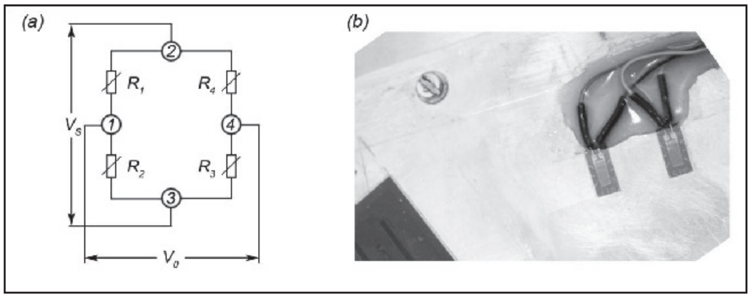

Figure 1. The Wheatstone “full bridge” strain gages circuit: a) block scheme, b) integrated strain gages

Full bridge sensor platform has the following advantages:

- With a mirror-imaged cross-section, normal strains are compensated.
- The magnitudes of changes to strain gages which are located in adjacent bridge arms in the circuit are subtracted.
- Thermal strains are compensated to a high degree.
- Interference effects through internal bridge connections are largely suppressed.
- The change in AC voltage level is very suitable for measuring the signal of vibration.

The disadvantage of this type of sensor is its low output voltage level. This type of measurement must be considered in conjunction with the signal amplifier system. The signal amplifier's primary task is to raise the level of the bridge circuit's output signal $y(t)$ from the millivolts to volts region [6]. The gain of sensor signal amplifier is the part of overall active vibration control system gain.

Piezoelectric actuator MIDE QW10p for active vibration control is used. Location of the actuator at the plate is presented in Figure 2, thus optimization problem is reduced to finding optimal orientation of the actuator.

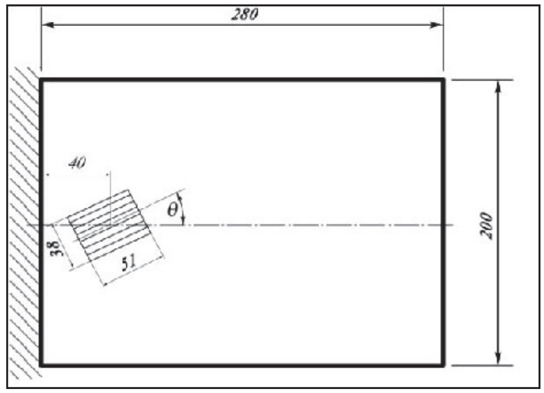

Figure 2. Cantilever aluminum plate with piezoelectric actuator

Hence, position and orientation of piezoelectric actuator should be such that it gives good controllability to controlled modes. A fuzzy optimization approach based on the pseudogoal function for multi-objective problem is proposed in [5], and objective functions have to be maximized as a pseudogoal function in the form of the fuzzy number. According to the fuzzy decision principle [7], the fuzzy decision is defined as the intersection of fuzzy objectives and the optimum solution can be selected by maximizing the smallest membership function. Figure 3 represents the membership degrees for the first three modes versus orientation angle. From Figure 3 it can be concluded that the best solution is achieved for angle $\Theta = 25^0$.

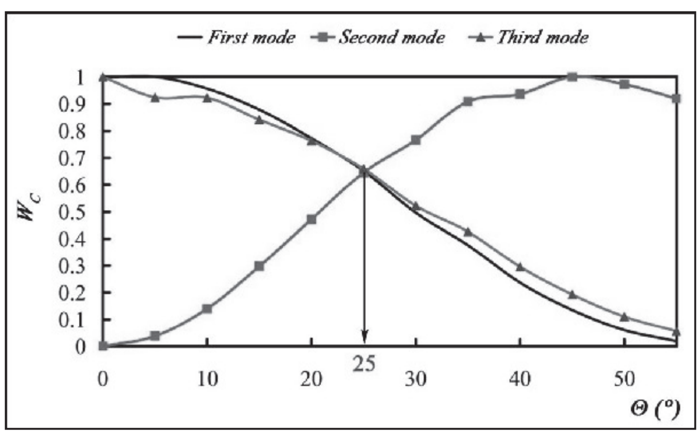

Figure 3. Membership degrees for the first three modes versus orientation angle.

Active vibration control system design

The active vibration control system was developed for active damping around the resonance frequencies. The system has four main subsystems: a) control subsystem, b) integrated structure, c) high-voltage amplifier and d) disturbance system. Schematic diagram of the designed system depicts in Figure 4.

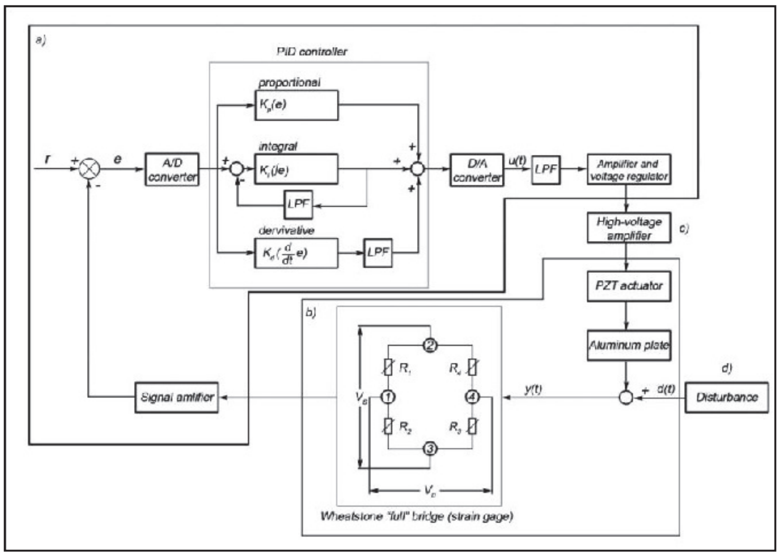

Figure 4. Active vibration control system block diagram

The Wheatstone "full" bridge (120Ω strain gages) is used to detect the signal, $y(t)$. The signal then goes to control subsystem. The first task is to amplify the sensor milivolts signal in region of volts. This is realized with instrumentation amplifier AD623AN with matched gain of 200. In system the output signal is the error, because the desirable reference input is zero, $r(t) = 0V$, the plate needs to be in neutral position. The error signal, $e(t) = -y(t)$, passes through 16 bits A/D convertor LTC1864 and discrete signal come in PID control implemented on PIC32MX440F256H microcontroller. The PID control algorithm is explained in the previous section. Discrete control signal comes in 16 bits D/A convertor DAC8523 and its analog values $u(t)$ passes thought low-pass filter to neutralize signal noise from D/A convert process. The analog control signal $u(t)$ flows through one more signal amplifier and the voltage regulator with primary function to prevent the voltage of control signal goes across the range of -5V to 5V. The signal finally passes through a PDA X3 high voltage amplifier before arriving at the actuators and the control signal is amplified by factor of 40. The input voltage of high voltage amplifier is limited between -5V to 5V.

Fig. 5 presents a schematic diagram of the vibration active damping experimental setup considered in this study.

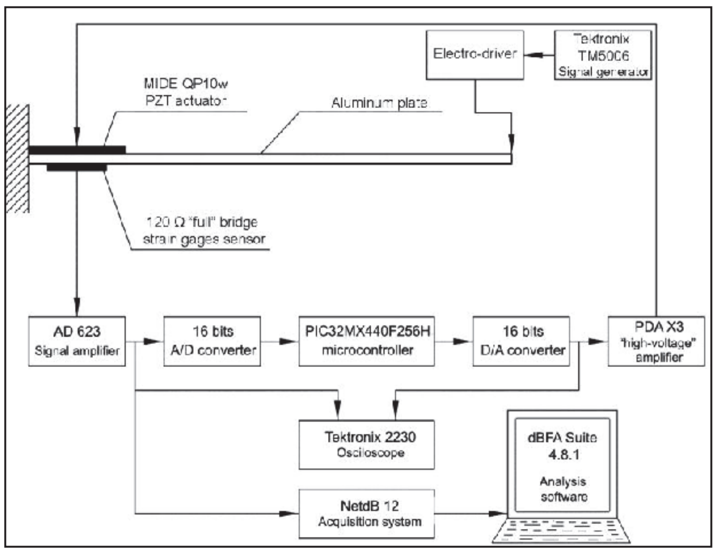

Figure 5. Schematic diagram of experimental setup.

Results

In this section, the results of thin aluminum plate vibration active damping system via PID feedback controller are presented. The experimental results are given in time and frequency domains.

This section considers the case of periodic excitation on first bending resonant frequency of the plate, which is 11.8 Hz.

Proportional, integral and derivative gains of the proposed PID are obtained by using the Ziegler-Nichols method. In Ziegler-Nichols method, the important step is the determination of critical gain (gain margin of the closed-loop system). 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. Periodic excitation is set on first resonant frequency.

In open-loop (uncontrolled), control signal is clipped in order to prevent voltage input in high voltage amplifier to be out of -5V till 5V range. In closed-loop (controlled), the control signal with range from -2.5V till 2.5V is adequate for full active vibration control (actuator voltage from -100V till 100V). In Figure 6 the frequency response of sensor signal by using FFT for uncontrolled and controlled cases is depicted.

In order to investigate how different values of proportional, integral and derivative factors affect control performances, an experiment was performed for several combinations of these factors. Table 1 presents the normalized root-mean-square (rms) sensor output voltage for uncontrolled case and each combination of factors as well a decrease in magnitude obtained by active vibration control.

It can be seen from Table 1 that control performances of PID controller are changed with variation of three factors. The higher active damping on first resonant frequency is realized with next factors: $K_p = 5.5$, $K_i = 0.040$, $K_d = 19$.

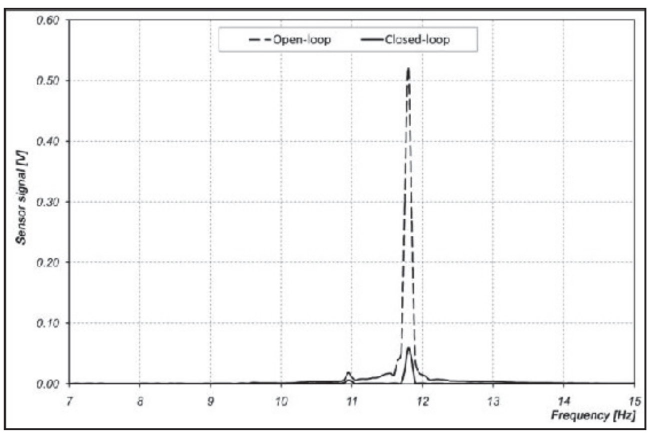

Figure 6. Frequency response by using FFT for controlled and uncontrolled cases

Table 1.
Normalized rms sensor output voltage for different factors and decrease in magnitude

K_p	K_i	K_d	Magnitude at first resonant mode (V)	Damping at first resonant mode (%)

Uncontrolled			0.51990	/
4.5	0.055	14	0.05899	88.65
4.5	0.050	14	0.06021	88.41
4.5	0.050	15	0.05836	88.77
4.5	0.050	16	0.05028	90.32
4.5	0.050	19	0.05575	89.28
4.5	0.040	19	0.06185	88.10
5.5	0.040	19	0.04658	91.04

However this is not true proposition, because the control is unstable and amplitudes are increased on second natural frequency. The effect of spillover is achieved (Figure 7).

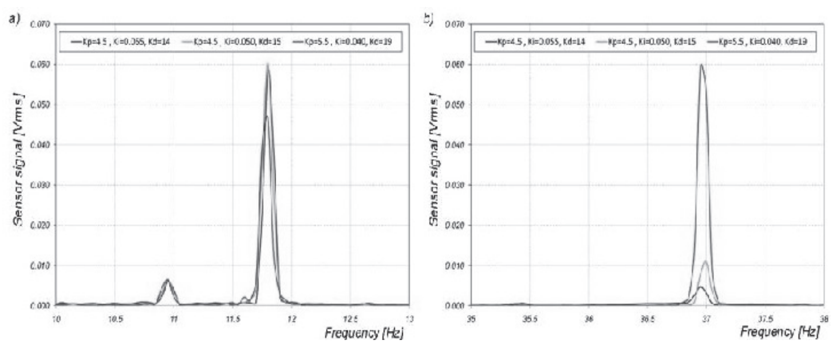

Figure 7. The frequency response of sensor signal by using FFT for different values of PID factors: a) first resonant frequency, and b) second resonant frequency

Conclusion

This work has presented the design, development and experimental verification of the active vibration control system. The approach of use the strain gages like sensor platform, PZT materials for actuation and PID controller for active damping problems are verified on flexible aluminum plate with considerable suppression level.

As it can be seen from paper, the developed active vibration system based on PID algorithm control reduces the vibration of the plate at resonant frequency with high level of effectiveness. The PID controller was tuned by Ziegler-Nichols method choosing convenient values for controller parameters (i.e., the critical gain K_{cr} and period P_{cr}) with recommended for fine additional tune. Those corrections must be carefully tuning without any perturbation of stability margin.

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