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Hardware Implementation of High-Speed Active Vibration Control System Based on DSP320C6713 Processor

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Abstract : This paper deals with the experimental assessment of the vibration suppression of the smart structures. First, we have presented a new high-speed active control system using the DSP320C6713 microprocessor. A peripheral system developed is composed of a data acquisition system, A/D and D/A converters, piezoelectric (PZT) actuator/sensors, and drivers for fast data processing. Next, we have tested the processing time of the peripheral devices, and provided the corresponding test results. Since fast data processing is very important in the active vibration control of the structures, we have focused on achieving the fast loop times of the control system. Finally, numerous experiments were carried out on the aluminum plate to validate the superior performance of the vibration control system at different control loop times.

Key words : Active vibration control, DSP(Digital signal processing), PZT actuator/sensor, PPF control

1. Introduction

Recently, there has been widespread interest in the active vibration control system. Owing to the performance of the improved piezoelectric devices, a great deal of attention has been paid on the research and development of high-speed active control system integrated with PZT sensors/actuators and controllers. There have been a large number of theoretical papers for vibration control of the cantilever beam and thin-plate beam. However, few papers have considered the active control system with fast processing microprocessors, experimentally.

A control system using VME bus processor was presented for vibration control of the thin-plate[1]. Also, there has been an experimental result on real-time control for a rectangular steel plate incorporated with ADSP21062 EZKI and EZ_ANC II digital-signal-processing (DSP)[2]. In addition, Chu et. al. had designed a simulator using real-time active controller with TMS320C40 DSP board[3]. The active

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controller has been proposed for cylinder shell structures, integrated with PZT driver and TMS320C30 DSP using PPF controller and filtered-x LMS controller[4]. Further, the active controller for steel plate with 340x300x0.5 [mm^3] in dimension has utilized DSP320C30 DSP featuring multi-adaptive feed-forward control inputs[5].

According to many papers presented so far, they had adopted fast processing microprocessors for the vibration control system. It is implied but not proven that the active control system with fast processing offers better performance in vibration suppression. In this study, to prove this experimentally, we have developed a new active control system adopting fast microprocessor in DSP320 series with peripheral devices high-speed A/D and D/A converters, and a new PZT driver.

2. Design of DSP-based Control System

In PZT materials there is coupling between the electrical and mechanical constitutive relationships. Note that PZT materials generate an electric charge proportional to applied stress, which makes them a natural sensor. Conversely, PZT materials can be effectively used as an actuator, as they deform when an electrical charge is applied. As a result, they can be used in actuation and sensing. The general constitutive equations of linear-piezoelectric materials describe a tensor relation between mechanical and electrical variables in the form[4]

$$S = s^E T + dE \tag{1}$$

$$D = dT + \varepsilon^T E \tag{2}$$

where S is the mechanical strain, T is the mechanical stress, E is the electrical field, D is the electrical displacement, S^E is the mechanical compliance of the material measured at zero electric field ($E=0$), ε^T is the dielectric permittivity measured at zero mechanical stress ($T=0$), and d is the piezoelectric coupling between the electrical and mechanical variables.

Referring to Fig. 1, an active control system is composed of a high-speed plus relatively low-priced DSP320C6713 processor whose processing speed is 1500 [MPLOPS]. In other words, its processing speed is 27 times faster than the DSP320C30 processor, and its detailed specifications are described in Ref. 7. Also, we have developed an interface system based on A/D and D/A converters providing extremely high-speed processing and resolutions. More explicitly, the complete actuator system is consisted of the PZT driver and elements: the PZT driver is intended to amplify control signals from the DSP board up to ±400[V] for the actuating elements, and the PZT sensor detects the amplitude of vibration and transmit it to the DSP control board via the A/D converter. The PZT actuator/sensor used is NASA M8557 S1 type, and its specification is described in Ref. 8 and Table 1.

In this study the interface system to communicate with external devices includes

A/D converter for sensing signals from PZT device and D/A converter for receiving signals from PZT actuator driver. They are ADS7805 and DAC712 chips charactering 16 bit resolutions, respectively. Fig. 2 depicts the I/O interfaces ensuring communication with the main controller, A/D and D/A converters. The PZT driver amplifies control signals of the main controller to execute active control action up to PZT driving voltage. In the study, we have utilized a new bridge driver developed and a PA97 commercial driver manufactured by APEX Corp. as the actuator amplifier. Now, the structure and configuration of the complete control system are shown in Fig. 1 and Fig. 2, respectively. The PZT sensor is connected to the input port of the A/D converter wired to the DSP chip whose data and address buses are further connected to data ports of the D/A converter. Analog output ports of the D/A converter are connected to the input ports of the PZT actuator amplifier, and the output ports of the non-inverted amplifier are now linked to the input ports of the PZT actuator amplifier.

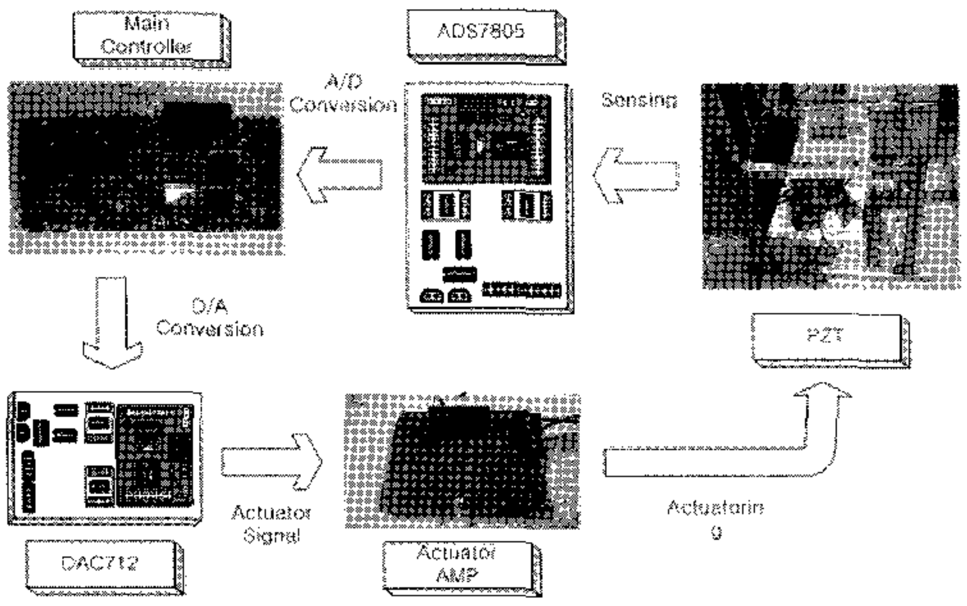


Fig. 1 Schematic diagram of system using DSP320C6713 chip

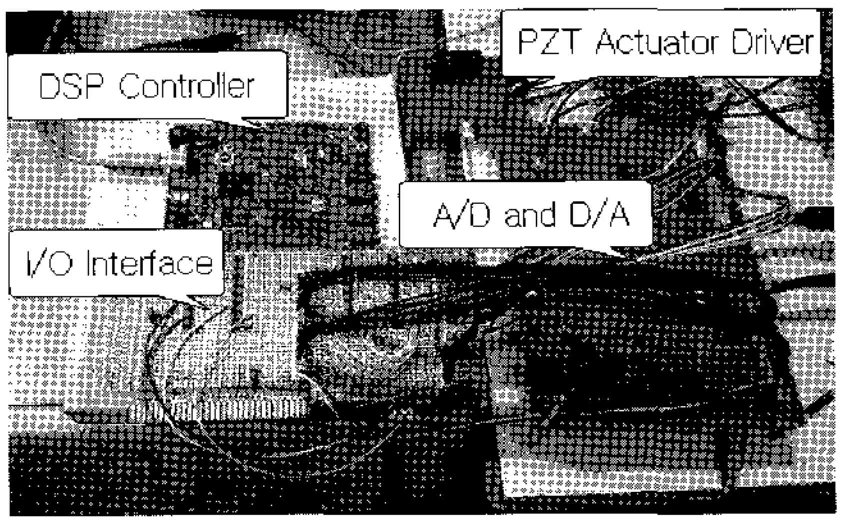
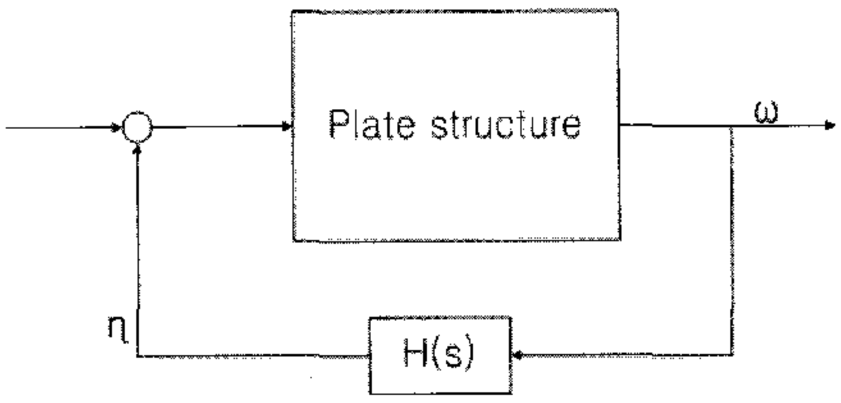


Fig. 2 Experimental setup of control system



ω : natural frequency for structure
η : mode of controller

Fig. 3 Block diagram of controller

3. Performance test of control system

The model equation of the plate structure is expressed as 2nd differential equations. In thei paper, the first mode of the plate structure is controlled. When sensors/actuators are arranged in a collocated way, the so-called positive position feedback (PPF) is extensively used in practice. In the framework of the PPF design methodology[9], [10], the block diagram of the control system (Fig. 3) and the control algorithm for the single-input single-output (SISO) is described as

$$H(s) = \frac{\omega_f^2}{s^2 + 2\zeta_f\omega_f s + \omega_f^2} \qquad (3)$$

where ω_f, ζ_f, T_s are natural frequency, damping ratio, and sampling rate for the compensated circuit (or controller), respectively. Generally, PPF controller achieves active control of frequency by resonance of ω_f.

Equation (4) is bilinear transform for digital control system.

$$s = \frac{2}{T_s}\frac{z-1}{z+1} \tag{4}$$

The use of a digital control system requires the transformation of the time-continuous equation into its time-discrete form. Substituting (4) into (3) using bilinear transform leads to

$$H(z) = \frac{b_2 z^2 + b_1 z + b_0}{z^2 + a_1 z + a_0} \tag{5}$$

where

$$a_0 = (4/T_s - 4\zeta_f \omega_f / T_s + \omega_f^2)/\Omega,\quad a_1 = (2\omega_f^2 - 8/T_s^2)/\Omega$$

$$b_0 = \omega_f^2/\Omega,\quad b_1 = 2\omega_f^2/\Omega,\quad b_2 = \omega_f^2/\Omega$$

$$\Omega = 4/T_s^2 + 4\zeta_f \omega_f / T_s + \omega_f^2$$

Then the discrete form for the control algorithm (5) is described in a simple iterative procedure referring reference[6] as

$$u_k = -a_1 u_{k-1} - a_0 u_{k=2} + b_2 (y_k + 2y_{k-1} + y_{k-2}) \tag{6}$$

where y_k represents the sampled output of the sensor and u_k is the calculated control input.

It is known that feedback control using PPF compensator will accomplish the addition of damping to selective modes, see Baz et al. Note that the PPF controller is a highly damped second order low-pass filter that can be tuned to resonate at a flexible structure's natural frequency, much like a tuned mass damper[11]. This compensator could be tuned such that the natural frequency of the compensator (or filter) corresponds to the excitation frequencies, rather than natural frequencies of the structure, and thus provide effective vibration cancellation. At low frequencies this controller adds flexibility and at high frequencies it adds stiffness to the structure. Moreover it also tends to split the vibration modes.

In this paper, we adapted the NASA M8557 S1 type actuator and applied it to the control system whose specification is given in Table 1.

Table 1 Specification of M8557 S1

Overall dimensions	110mm x 75mm (4.3" x 2.9")
Active area (actuator)	85mm x 50mm (3.4" x 2.0")
Active area (sensor)	85mm x 3.5mm (3.4" x 0.14")
IDE Spacing	0.5 mm (20 mil)
Capacitance	Approx. 12nF
PZT type	Navy Type II
Max voltage	-500V to +1500V
Max tensile strain	4500 ppm

3.1 Sensing test of PZT device

As illustrated in Fig. 3, M8557 PZT actuator/sensor is glued to the rectangular aluminum plate supported by the two ends. The plate thickness is 1.5[mm], and its overall width is 210x400[mm^2] in dimensions. The signal of the PZT sensor was measured by the 400[MHz] digital oscilloscope, and ±5[V] test input signal with 10[Hz] period was applied using the function generator, and then it was amplified to ±100[V], and the output sensor signal from the PZT was measured as ±2[V] as shown in Fig. 4.

The amplified test signal was applied to the PZT actuator, and the voltage signal of the sensor on the vibrated plate was measured. At the rising and falling edge of the step input pulses, the negative and positive sensor signals were measured, respectively. As expected, structural vibration with chattering occurred, and it decreased as time passed. Through the experimental tests, we have found that the ratio of the actuator input voltage to the sensor output voltage is approximately 1/100.

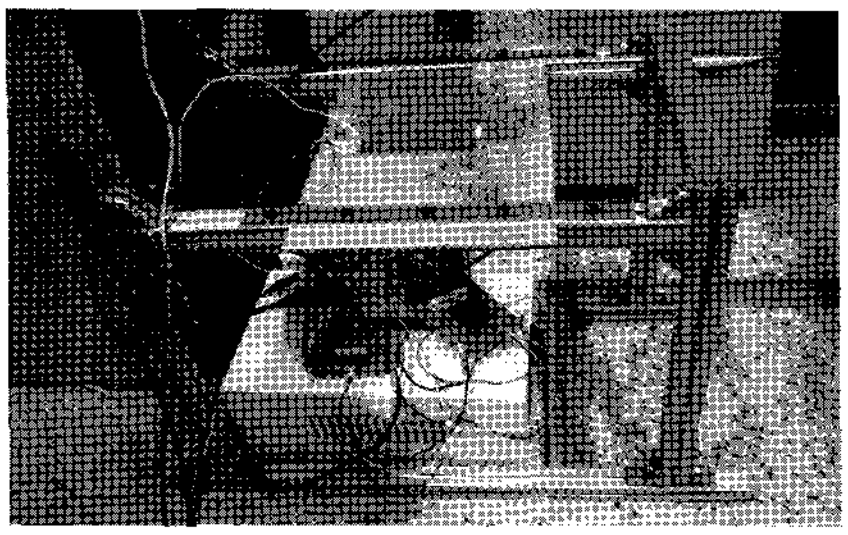


Fig. 4 Test bed for vibration control system

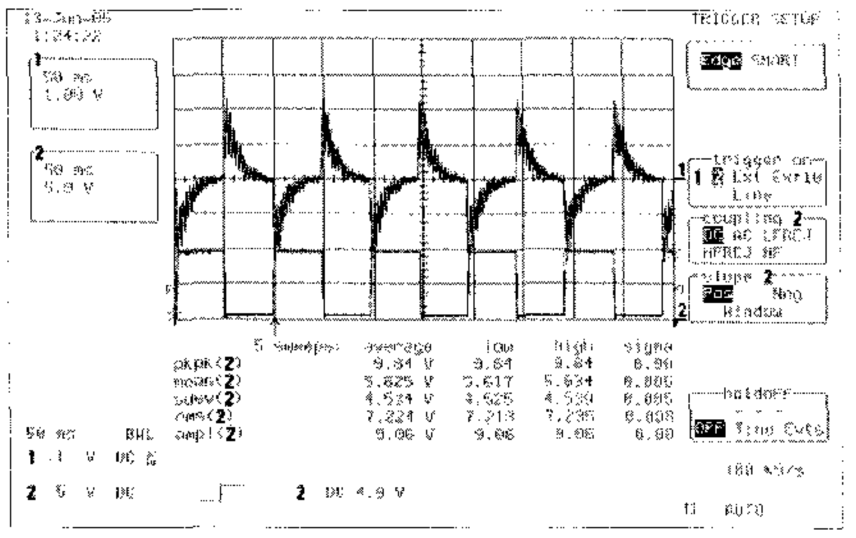


Fig. 5 100[V] test input with 10Hz(50ms)

3.2 Performance test of drivers

The DSP processor receives the digital signal converted from the analog sensor signal by the A/D converter. According to the control algorithm, the control signal is converted into the analog signal through the D/A converter, which is amplified and put into the PZT actuator. Note that the PZT actuator requires high voltage for actuation. We prepared two kinds of drivers for PZT actuators; one is the bridge driver we developed using transistors and the other is the commercial driver PA97 as illustrated in Figs. 5 and 6, respectively.

The test results of the drivers are presented in Figs. 7 through 10. Note that Figs. 7-8 and 9-10 show the output of the bridge driver and PA97, respectively. In this study, the bridge driver has been developed to minimize the time-delay over amplification of the input signal. For the performance test of the bridge driver, a voltage of 5[V] from the function generator was applied to the bridge driver as a step input and an amplified 50[V] was generated as the output. As shown in Figs. 7 and 8, the frequencies of the input signals are 50[kHz] and 200[kHz]. The processing time over amplification was measured using 400[MHz] oscilloscope. In the figures, the lower curves are the input signals and the upper ones are the output signals. According to the tests results, the whole processing time takes only less than 1 [μs], which is amazingly fast response and is enough for real time processing.

Also, a new driver using the PA97 commercial device has been designed to supply the high voltage to the actuator, and its capability is tested in amplifying the voltage and processing time. Further we tested the processing time from the sensor to the amplified signal of the devices, illustrated in Figs. 9 and 10, where the lower and upper ones represent the sensor signal and the amplified signal, respectively. Fig. 10 clearly gives the delay time. 5[V] clock pulse with 5[kHz] using the function generator was applied to the A/D converter. Each row line in the upper plot represents 50[V] and in the lower describes 5[V]. The processing time between A/D converter and the amplifier took 24.5[μs], where A/D conversion, D/A, and amplifier took 10[μs], 2[μs], and 12.5 [μs], respectively. The amplifier has 8[V/μs] rate such that it took 12.5[μs] in amplifying the voltage up to 100[V], which is fast enough for active vibration control. Here, the processing time can be reduced by adapting faster peripheral devices.

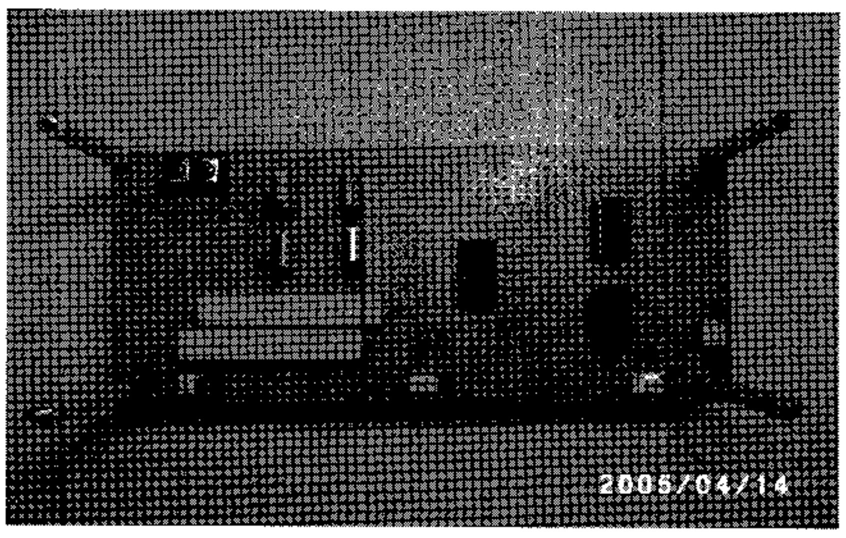


Fig. 6 Driver for PZT actuator using bridge circuit

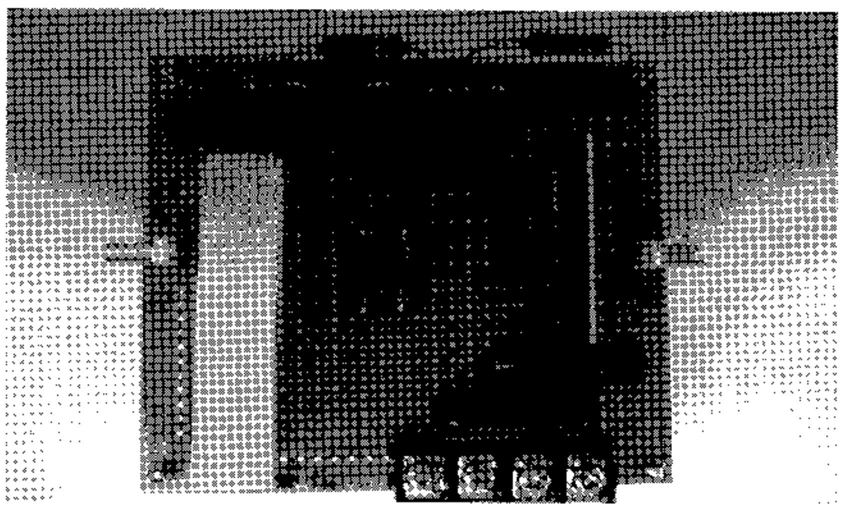


Fig. 7 Driver for PZT actuator using PA97

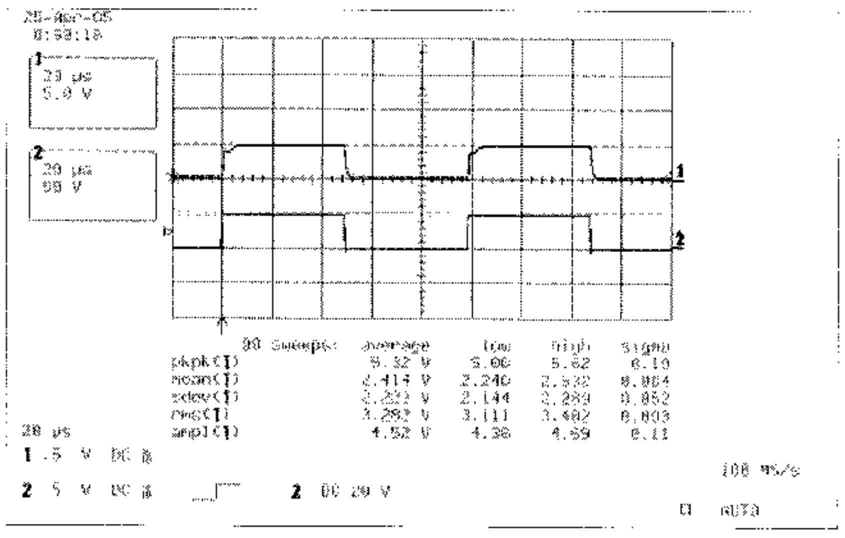


Fig. 8 Driver output at 50[kHz]

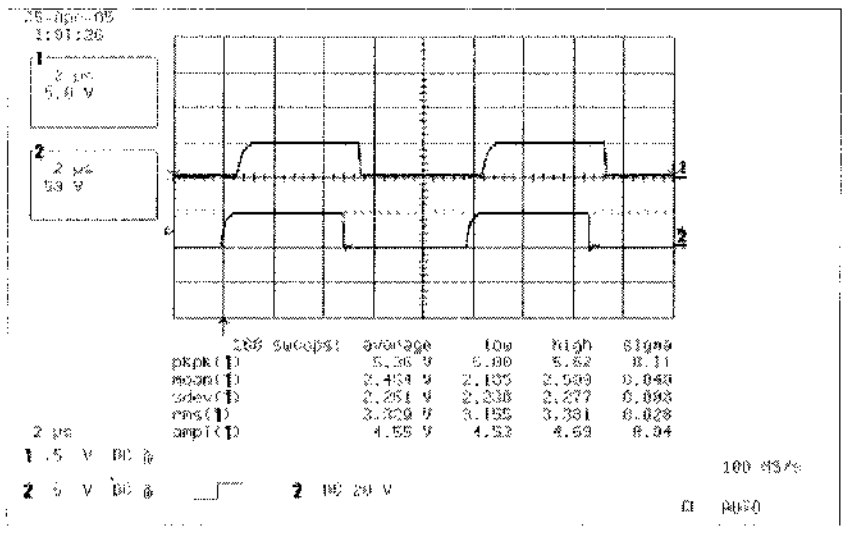


Fig. 9 Driver ouput at 200[kHz]

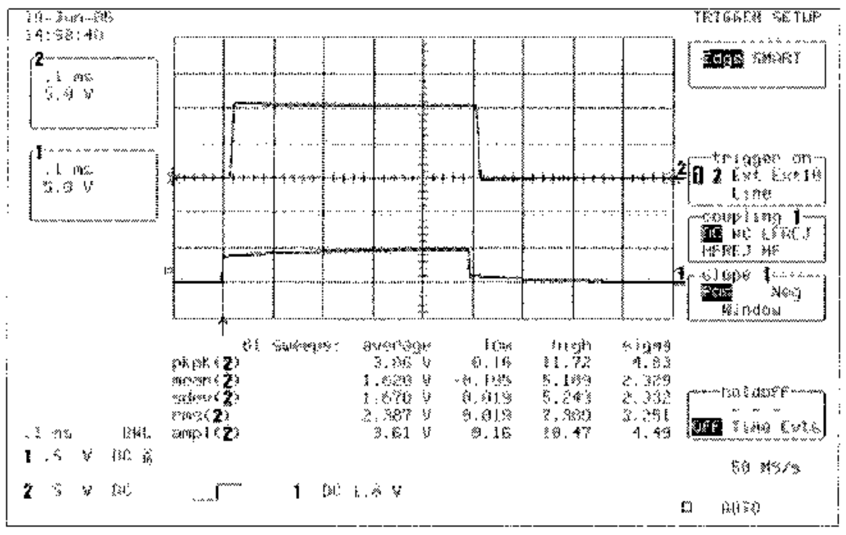


Fig. 10 Amp output at 1[kHz]

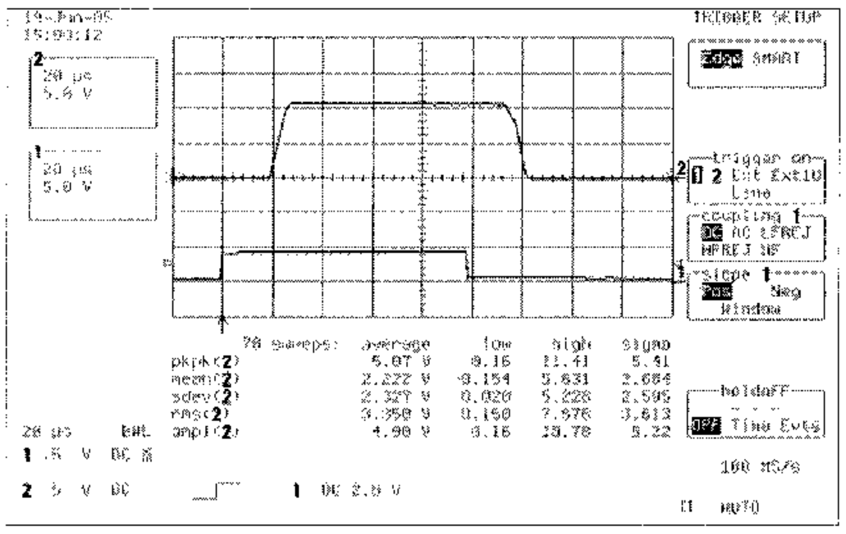


Fig. 11 Amp out at 5[kHz]

3.3 Test of active vibration control

Experiments were conducted to test the performance of the developed control system by applying PPF control algorithm, which is intended to reduce the vibration mode of the aluminum plate. An impulsive force is applied to the plate as a test signal. Also, two experimental tests with different loop times were performed to demonstrate the capabilities of the DSP320C6713 processor, as shown in Figs 11-14. Here, we provide performance comparisons the controlled and uncontrolled systems.

Through the mode tests of the plate, it is observed that the frequencies of first and second modes are 67[Hz] and 124[Hz] using FFT analyzer, respectively. In particular, we applied the PPF control algorithm to reduce the second mode. The control system with different loop times was tested to see the effect of the fast processing capability on the system. The TMS320C6713 processor is about 27 times faster than TMS320C32 chip, which has been used in many active vibration control test so far. Note that three loop times of 30[μs], 200[μs], and 500[μs] were applied in the tests. Fig. 11 gives the magnitude of the second mode, 92.1[dB] in the uncontrolled system. In the controlled system, the results show 90.3[dB] at 30 [μs] loop time, 90.6[dB] at 200[μs] loop time, and 91.7[dB] at 500[μs] loop time. Consequently, it is identified by the fact that the active control system shows better vibration reduction performance with faster loop times.

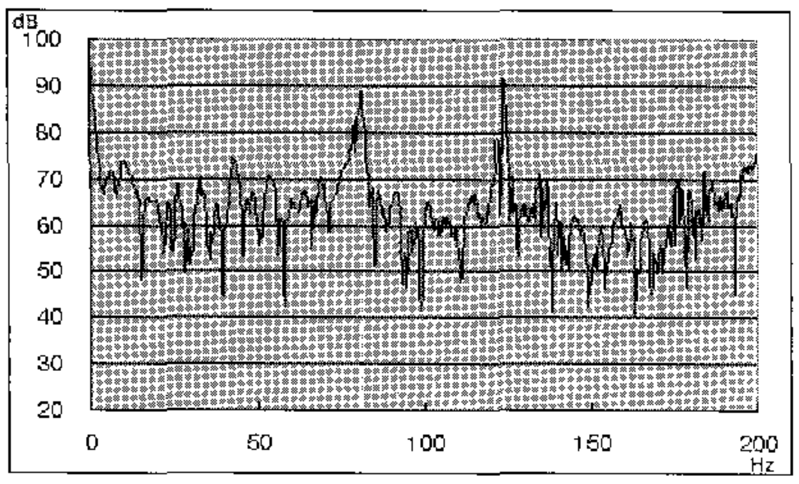


Fig. 12 The mode of uncontrolled system

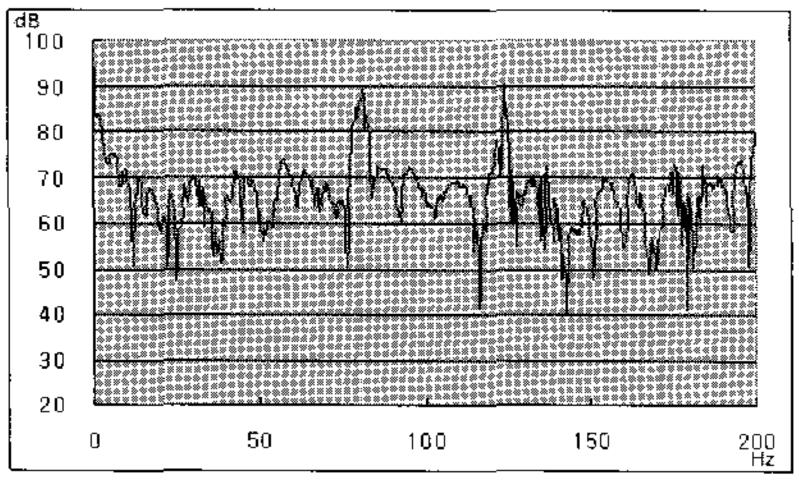


Fig. 13 Control loop time : 30[us]

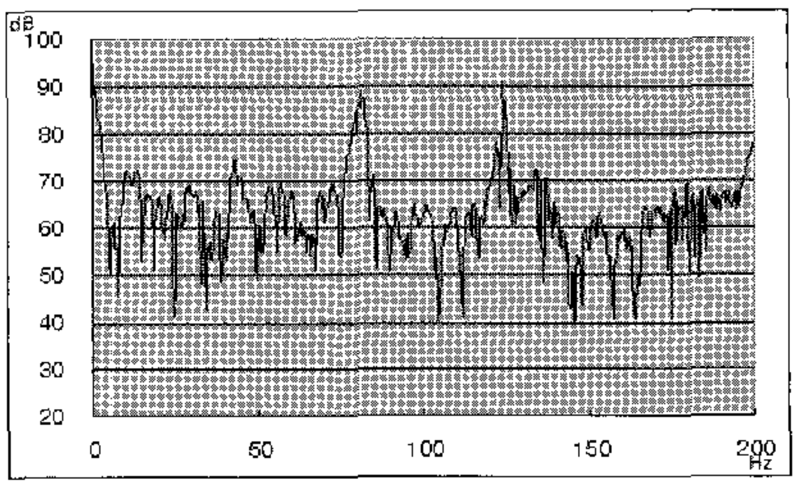


Fig. 14 Control loop time : 200[us]

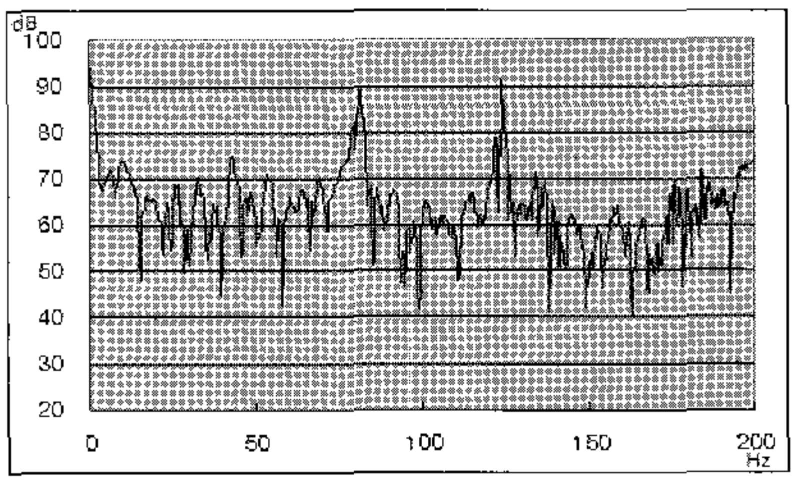


Fig. 15 Control loop time : 500[us]

4. Conclusions

In this paper, a new high-speed active control system has been developed to suppress the vibration of the rigid structure. The complete control system using PZT sensor/actuators is incorporated with the fastest DSP320C6713 microprocessor and peripheral devices such as A/D and D/A converters, and amplifier. Using the developed system, we have tested the processing time of the processor and peripheral devices for the speed of the loop times. It is observed that the overall processing time was fast enough to control the vibration mode of the prepared aluminum plate. Also, we have presented additional test results with different loop times to identify the superior performance of the DSP320C6713 processor in the fast processing time. In particular, we have applied the PPF control algorithm to reduce the specific vibration mode of the plate, and provided the test results on the control system with different loop times. Further, we identified that the vibration control system shows good vibration reduction. Faster loop time shows better results in vibration suppression. Accordingly, it is ensured that the proposed control scheme using DSP320C6713 would be a prospective control system in active vibration control of structures.

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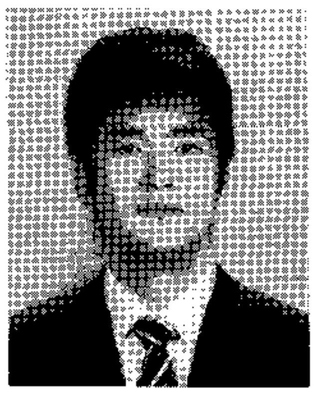

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