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Letter to the Editor

Vibration reduction of a CD-ROM drive base using a piezoelectric shunt circuit

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1. Introduction

The optical disk drives as the information storage device (ISD) are classified by CD-ROM, CD-R/RW, DVD-ROM/RAM/RW and so on. Especially, the CD-ROM drive has been widely used as a secondary ISD such as computer peripherals. The typical CD-ROM drive consists of the disk loading system, the feeding system including optical pick-up and spindle, the printed circuit board, and the drive base. The track density and the linear density of the disk are about 16,000 TPI (tracks-per-inch) and 43,000 BPI (bits-per-inch), respectively. To achieve high capacity of the CD-ROM drive, accurate position control of the optical pick-up head, fast access time, high rotation speed of the spindle, and vibration suppression of the feeding system are demanded. The vibration of the feeding system, which is affected by unbalanced flexible disk with high rotating speed and external excitation to the main base, leads to critical mechanical problem restricting the tracking and focusing servo performance. Consequently, anti-vibration of the feeding system is an urgent problem to be solved to achieve high capability of the drive [1,2]. Normally, conventional drives adopt passive rubber mounts to prevent the feeding system from external excitation and the vibration of the spindle. In addition, auto ball balancer is often used [3], and a semi-active mount using electro-rheological fluid has been also studied in order to overcome the limit of the passive rubber mounts [4]. The CD-ROM drive base, which has a role of supporting the feeding system, is easily exposed to environmental vibration sources such as user's handling and high-speed rotating disk. If the vibration of the main base is not effectively reduced, the robust servo control of the optical pick-up cannot be guaranteed. However, research activities on the vibration characteristics analysis for the drive are only concentrated upon the vibration suppression of the feeding system. The study about the dynamic characteristics of the CD-ROM drive base is considerably rare.

Consequently, the main objective of this work is to present the vibration suppression of the CD-ROM drive base using the piezoelectric damping integrated with shunt circuit. The piezoelectric

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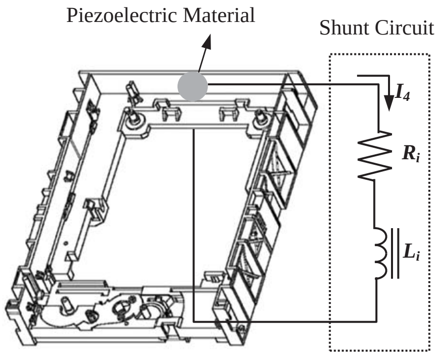
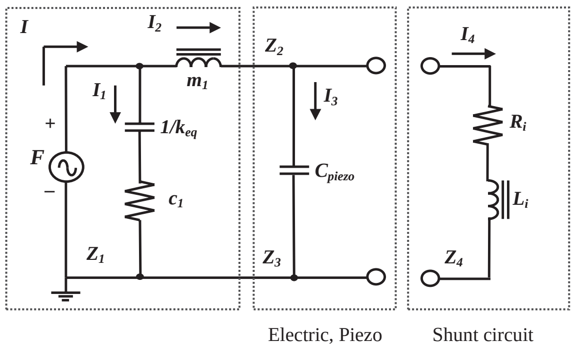
damping can be accomplished by converting mechanical energy of vibrating (or exciting) structure to electrical energy, which is then dissipated by heating in the external shunt circuit networked to the piezoelectric material [5–8]. In this work, we first derive displacement transfer function of the CD-ROM drive base in order to determine circuit values in an optimal way. The finite element analysis is followed to determine the target vibration mode to be suppressed. The shunt circuit connected to the piezoelectric is then experimentally realized, and vibration suppression performance is evaluated in both frequency and time domains. It is remarked that so far no research on the piezoelectric shunt circuit method applied to complex CD-ROM drive base has been reported.

2. System modelling

It is known that each resonant mode of the smart structure integrated with the piezoelectric shunt circuit can be modelled by mechanical vibration absorber that is one of very effective vibration reduction methods [5]. The mechanical vibration absorber is then modelled by an electrical impedance model via mechanical–electrical circuit analogy. Fig. 1(a) presents a



(a) Schematic diagram of the proposed model



(b) Equivalent electrical model

Fig. 1. The proposed model consisting of the structure-shunt circuit-piezoelectric material.

schematic diagram of the proposed whole system that consists of the structure (the CD-ROM drive base) with piezoelectric material and resonant shunt circuit. When the serial inductor–resistor circuit is considered, the electrical impedance model equivalent to the proposed system can be represented by Fig. 1(b). The m_1, k_{eq} and c_1 represent the mechanical characteristics of the inherent structure such as mass, stiffness and damping, respectively. The Z_i is impedance of each node given by

$$\begin{aligned} Z_1(s) &= k_{eq}/s + c_1 = k_{eq}/(\mathrm{j}\omega) + c_1, \\ Z_2(s) &= m_1 s = \mathrm{j}\omega m_1, \\ Z_3(s) &= 1/\left(sC_{piezo}\right) = 1/(\mathrm{j}\omega C_{piezo}), \\ Z_4(s) &= L_i s + R_i = \mathrm{j}\omega L_i + R_i. \end{aligned} \tag{1}$$

In the above, s is the Laplace variable. The electrical impedance model, of course, can be integrated with the specific vibration mode (modal frequency) to be reduced as shown in Fig. 2. It is clearly seen that the model shown in Fig. 2 can be considered as a single-degree-of-freedom system. The modal velocity of the proposed model with the piezoelectric shunt circuit can be expressed in the Laplace domain as

$$v(s) = \frac{F(s)}{\left\{Ms + (K/s) + Z(s)\right\}}. \tag{2}$$

Hagwood and Flotow [5] derived the mechanical impedance of the piezoelectric material as well as that of the shunt circuit, and found the transfer function of the displacement transmissibility by applying the mechanical impedance to the mechanical vibration absorber as follows:

$$\begin{aligned} &\frac{x}{x^{ST}} = \frac{\gamma^2 + \delta^2 r\gamma + \delta^2}{(\gamma^2 + 1)(\gamma^2 + \delta^2 r\gamma + \delta^2) + K_{ij}^2(\gamma^2 + \delta^2 r\gamma)}, \\ &\gamma = s/\omega_n^E, \quad r = R_i C_{pi}^s \omega_n^E, \quad \delta = \omega_e/\omega_n, \quad \omega_e = 1/\sqrt{L_i C_{pi}^s}. \end{aligned} \tag{3}$$

Here L_i and R_i are parameters of the shunt circuit to be desired, C_{pi}^s is the inherent capacitance of the piezoelectric shunted at constant strain. ω_n and ω_e are mechanical and electrical natural frequency of the inherent structure and shunt circuit, respectively. In addition, K_{ij} is the generalized electromechanical coupling coefficient, and x^{ST} is the static displacement of the system. ω_n^E will be defined in Eq. (6)

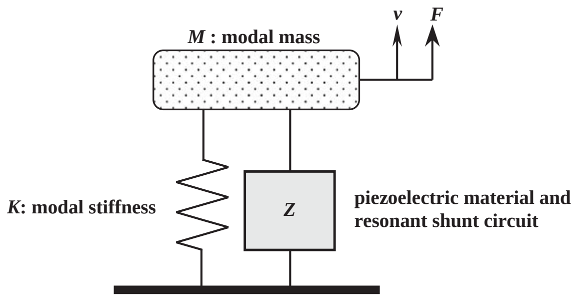
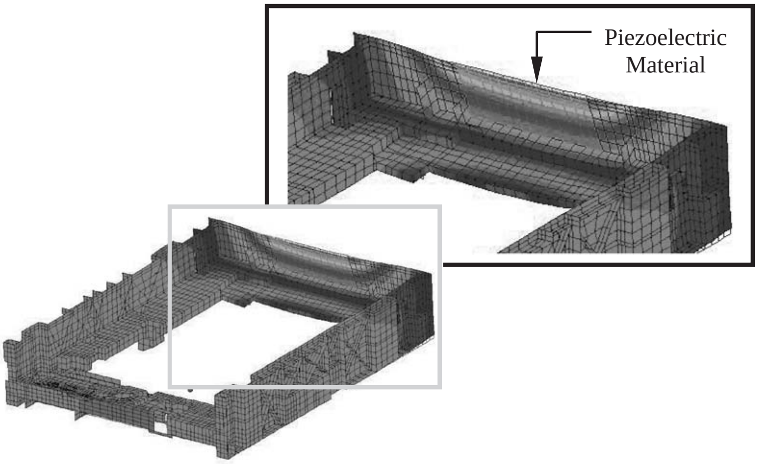
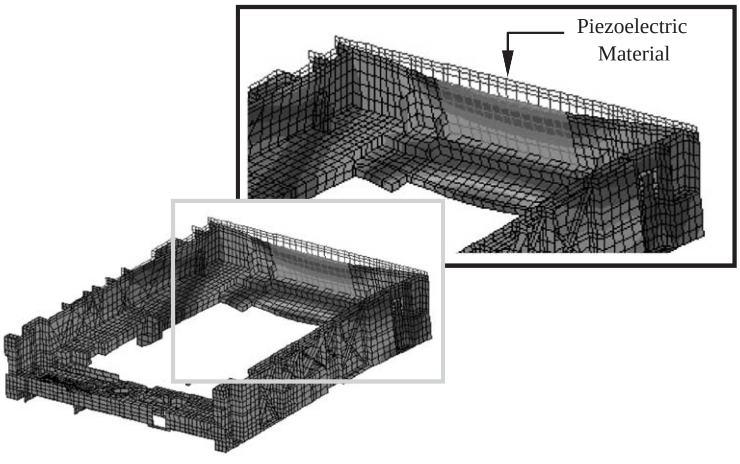


Fig. 2. Vibration absorber model integrated with the piezoelectric shunt circuit.

In this work, the finite element method (FEM) is used for modal analysis. In order to undertake this, commercial FEM program, NASTRAN has been employed. The modal analysis has been undertaken through two phases. Firstly, we investigate the modal analysis results in working frequency region for the original CD-ROM drive base, and choose a target mode shape, which exhibits the most severe vibration characteristics. In the second phase, the PZT considering the deformation of the target mode shape is integrated to the drive base and modal analysis is performed again. Fig. 3 presents the analyzed mode shapes of the modified CD-ROM drive base with the PZT. We see from this figure that the rear of the base is more deformed than other parts of the drive base at the second mode of 336 Hz. Consequently, the target frequency for vibration reduction is determined as the second mode.



(a) First mode (232Hz)



(b) Second mode (336Hz)

Fig. 3. Mode shapes of the modified CD-ROM drive base.

Prior to integrating the shunt circuit to the modified drive base, design parameters of the shunt circuit are tuned optimally by using Eq. (3). The first step in this tuning process is to make the fixed points in the transfer function. The next is to make the slope of the transfer function curve zero at both fixed points, 'optimum damping'. This process gives the optimum tuning parameter δ^* and the optimal circuit damping as follows [5]:

$$\delta^* = \sqrt{1 + K_{ij}^2}, \quad r^* = \sqrt{2}K_{ij}/(1 + K_{ij}^2). \tag{4}$$

Then, the optimal inductance and resistance are given by

$$L^* = 1/C_{pi}^S \omega_e^2, \quad R^* = r * /C_{pi}^S \omega_n. \tag{5}$$

The generalized electro-mechanical coupling coefficient K_{ij} in Eq. (4) is experimentally obtained [5,9]:

$$K_{ij}^2 = [(\omega_n^D)^2 - (\omega_n^E)^2]/(\omega_n^E)^2. \tag{6}$$

In the above, ω_n^D and ω_n^E are the natural frequencies of the structural mode of interest with open circuit piezoelectric material and short circuit piezoelectric material, respectively.

3. Experimental results and discussions

Now, we construct an experimental apparatus in order to demonstrate vibration reduction of the CD-ROM drive base using the piezoelectric shunt damping. Fig. 4 presents an experimental instrumentation adopted in this work. A carefully selected PZT is incorporated to the rear part of the drive base, which is equipped with vibration isolation workstation by fixture. The external excitation is applied to the drive base by employing input voltage to the PZT positioned to the fixture via signal generator and high voltage amplifier. The vibration of the drive base is measured by an accelerometer and analyzed by dynamic signal analyzer.

First of all, in order to verify the FEM analysis result, frequency response is measured in condition that the shunt circuit is open. From the measured frequencies shown in Fig. 5, the natural frequencies of the first and second modes are observed by 212 and 356 Hz, respectively.

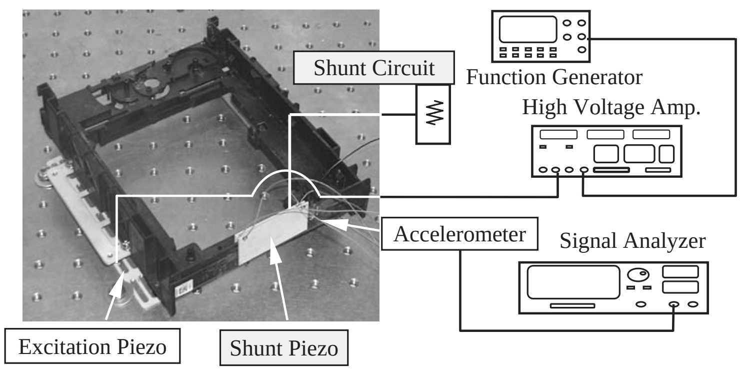


Fig. 4. Experimental apparatus for vibration suppression of CD-ROM drive base.

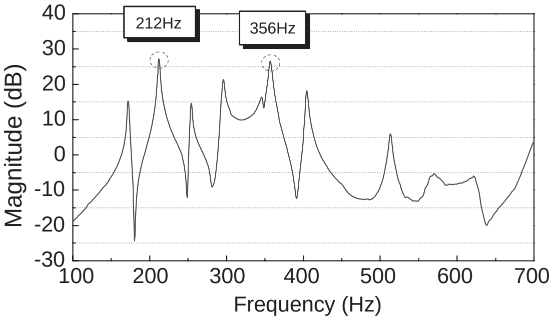


Fig. 5. Frequency response of the CD-ROM drive base in open circuit.

Table 1
Comparison of design parameters between analysis and experiment

Parameter	Analysis	Experiment
L^* (H)	5.10	4.85
R^* (Ω)	608.0	562.0
K_{31}	0.04	
C_{pi}^{S} (nF)	44.0	

The difference of the natural frequencies between the measurement and FEM analysis arises from the mismatched boundary conditions. In the next step, we investigate performance of vibration reduction using the piezoelectric shunt damping in target frequency region. The optimal parameter values such as inductance and resistance of the shunt circuit are determined using Eqs. (3)–(6), and then set for empirical realization. The amount of dissipated energy is determined directly from the resistance, and thus a proper choice of resistance is essential. Hence, the optimal resistance value is experimentally retuned. Table 1 compares analytically and experimentally obtained design parameters. The analytical values of optimal resistance and inductance parameter R^* and L^* are different from the experimentally obtained values as shown in Table 1. We see from Eq. (5) that the optimal values for the resistance and inductance in shunt circuit are directly affected by natural frequency. In addition, the inductor in the shunt circuit can affect the optimal resistance value and vice versa. This coupling effect between the resistor and the inductor is caused by electrical structure of synthetic inductor consisting of OP amps and resistors [8]. Fig. 6 presents the frequency response in region of target frequency of 356 Hz. It is clearly observed that the vibration reduction of 6.7 dB is achieved at the resonant peak by activating the shunt circuit. This result at the target mode is represented in time domain as shown in Fig. 7. When the shunt circuit is short, the magnitude of the acceleration is reduced from 21.7 to 10.1 m/s^2. In terms of the displacement, the vibration magnitude of 4.4 μm is reduced to 2.1 μm by activating the piezoelectric shunt circuit. Consequently, these experimental results demonstrate that the piezoelectric shunt damping can be effectively applied to vibration reduction of the CD-ROM drive base.

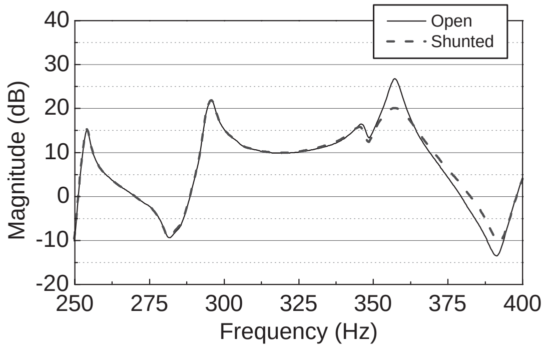


Fig. 6. Experimental result by piezoelectric shunt damping in frequency domain.

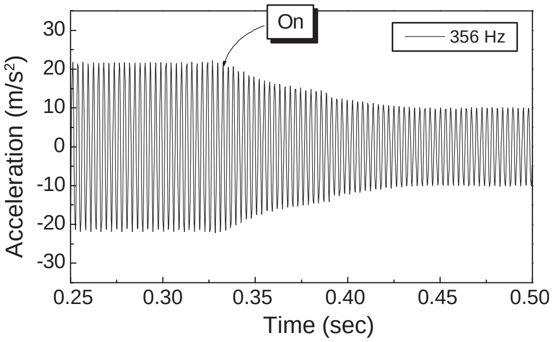


Fig. 7. Time response of the acceleration at target mode.

4. Concluding remarks

In this work, the piezoelectric shunt damping for vibration reduction of the CD-ROM drive base was proposed and its effectiveness was empirically demonstrated. After analyzing mode shape of the system via finite element analysis, the drive base was incorporated with the piezo shunt circuit and then the target frequency was determined. The mechanical vibration absorber method was used to tune optimal parameters of the shunt circuit and these values were adopted to the shunt circuit for the experimental realization of the CD-ROM drive base. Experimental results prove that piezoelectric shunt damping is an effective approach to reduce undesirable vibration of the drive base. It is expected that vibration reduction by the piezoelectric shunt damping will give a significant improvement of the performance of the CD-ROM drive. Finally, it is remarked that multi-mode piezoelectric damping with one piezoelectric material for the CD-ROM drive base and improved method to decide more precise shunt circuit parameters will be undertaken as a second phase of this study.

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