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Multi-mode vibration reduction of a CD-ROM drive base using a piezoelectric shunt circuit

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Abstract

This paper presents a new design methodology for the piezoelectric shunt damping system and applies to the multimode vibration suppression of a CD-ROM drive base. Admittance is introduced to predict the performance of the piezoelectric shunt damping. Numerical admittance obtained by commercial finite element code, ANSYS, is compared with experimentally measured one and the effectiveness of the model is verified. Multimode piezoelectric shunt damping is experimentally realized based on the target mode and frequencies obtained by the admittance analysis. The vibration of the CD-ROM drive base is effectively reduced by activating the piezoelectric shunt circuits. The experimental results presented in this work prove that admittance of the piezoelectric structure is capable of predicting the performance of piezoelectric shunt damping.

1. Introduction

The optical disk drive (ODD), which can store and reproduce multimedia information such as audio and video, is a representative information storage device (ISD). Recently, CD-ROM and CD-R/RW classified as a first generation ODD and DVD-ROM/RAM/RW classified as a second generation ODD have been widely used as a secondary ISD such as computer peripherals. However, they are very sensitive to external vibration or impact because of high storage density and high-speed data transmission [1]. Therefore, it is very important to study the dynamic characteristics and vibration suppression of disk drives to improve the performance of ODD.

The typical CD-ROM drive consists of the disk loading system, the feeding system including optical pick-up and spindle, the printed circuit board (PCB), and the drive base. The objective lens of the optical pick-up, which is supported by flexible structure and operated by voice coil motor (VCM), has a capability of quick response and large operating bandwidth with very low current. However, it is very sensitive to internal and external excitations of the disk drive [2]. In order to achieve high performance of the CD-ROM, accurate position control of the optical pick-up head, fast access time, high rotation speed of the spindle are required and at the same time, vibration suppression of the feeding system is necessary. The vibration of the feeding system, which is affected by unbalanced flexible disk with high rotating speed and external excitation to the

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drive base, leads to critical mechanical problem restricting the tracking and focusing servo performance. 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 drive 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.

Authors studied vibration suppression of CD-ROM drive base using the piezoelectric shunt circuit [5]. The vibration of CD-ROM drive base was successfully reduced with the piezoelectric shunt damping. However, multimode piezoelectric damping and accurate design parameter are required to improve the piezoelectric shunt performance. The piezoelectric 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 materials [6–9]. To dissipate mechanical energy efficiently, mechanical energy in the piezoelectric structure must be transferred to electrical energy effectively. Therefore, the analysis of electro-mechanical characteristics of the piezoelectric structures is very important for the design and prediction of performance in the piezoelectric shunt system. In this paper, admittance is introduced to represent electro-mechanical characteristics of the piezoelectric structures, and it is shown that admittance in open circuit is proportional to dissipated energy in the shunt system. After that, admittance is used as a performance index in the piezoelectric shunt system. Admittance is obtained by experimentally and numerically using commercial finite element code. Finally, the performance of the piezoelectric shunt damping in CD-ROM drive base is realized by the experiments and vibration suppression is evaluated in both frequency and time domains.

2. Admittance in piezoelectric shunt system

Piezoelectric material has the ability to transfer mechanical energy into electrical energy and many researchers have studied passive damping of mechanical vibration/noise using piezoelectric shunt system [6–9]. The mechanism of piezoelectric shunt system can be divided into two part; first, energy transfer from mechanical system to electrical system, and second, dissipating the transferred electrical energy in shunt circuit. Therefore, the high performance of piezoelectric shunt system can be achieved by cost effective energy transfer from mechanical system to electrical system. Admittance of piezoelectric structure is known as a representative parameter of electro-mechanical characteristic in piezoelectric shunt system [10] and represents the ease with alternating current flow through a complex circuit system. In this section, the relationship between admittance in open circuit and dissipated energy is studied.

Fig. 1(a) shows a schematic diagram of the proposed CD-ROM drive base with piezoelectric shunt circuit. When the exciting frequency of piezoelectric structure is much lower than the natural frequency of piezoelectric materials, equivalent electric model of piezoelectric structure can be obtained as shown in Fig. 1(b). In the equivalent electric model, C_p is capacitance of piezoelectric material and L_1, C_1 and R_1 represent equivalent mass, spring and damping of CD-ROM drive base, respectively. Capital Z in Fig. 1(b) represents electrical impedance, and subscripts s, p and cir represent structure, piezoelectric material and shunt circuit, respectively. If shunt circuit is assumed as serial resonant circuit like Fig. 1, impedances of the equivalent electric model are expressed as follows:

$$
\begin{aligned}
Z_s(s) &= m_1 s + \frac{k_1}{s} + c_1 = j\omega L_1 + \frac{1}{j\omega C_1} + R_1, \\
Z_p(s) &= \frac{k_2}{s} = \frac{1}{j\omega C_p}, \\
Z_{\mathrm{cir}}(s) &= L_{\mathrm{cir}} s + R_{\mathrm{cir}} = j\omega L_{\mathrm{cir}} + R_{\mathrm{cir}}, \qquad (1)
\end{aligned}
$$

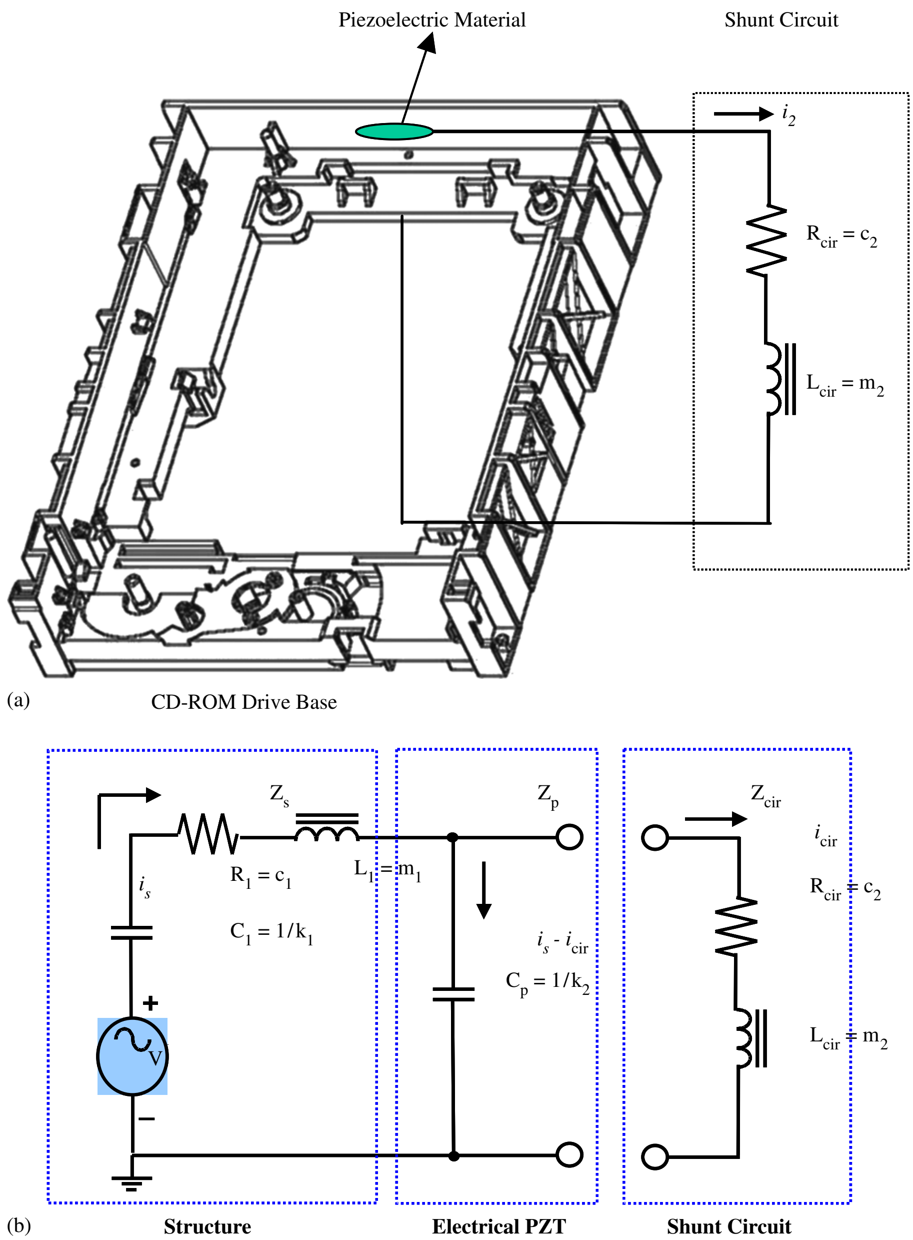

Fig. 1. The propose model consisting of the CD-ROM drive base with piezoelectric shunt circuit. (a) Schematic diagram of the proposed model, (b) equivalent electrical model.

where s represents Laplace variable. In open circuit, i.e. $z_{\text{cir}} = \infty$, total current of piezoelectric structure generated by the external force, I_O, is given as follows:

$$I_O = \frac{V_O}{(Z_s + Z_p)} = V_O Y_{sp}, \tag{2}$$

where $Y_{sp} = (Z_s + Z_p)^{-1} = I_O/V_O$ and represents admittance of piezoelectric structure in open circuit. When shunt circuit is connected to the structure, i,e. $Z_{\text{cir}} \neq \infty \neq 0$, the total current of piezoelectric shunt system can be expressed as follows:

$$I = I_s = I_p + I_{\text{cir}} = \frac{V_p}{Z_p} + \frac{V_{\text{cir}}}{Z_{\text{cir}}} = V_{\text{cir}}\left(\frac{Z_p + Z_{\text{cir}}}{Z_p Z_{\text{cir}}}\right). \tag{3}$$

If same external load is applied to the piezoelectric structure before and after connecting shunt circuit, total current generated in each system is same and can be expressed as $I_O = I$. From Eqs. (2) to (3), voltage applied

Table 1
Material properties of CD-ROM drive base and PZT-5H

CD-ROM drive base (ABS/PBT alloy)	
Young's modulus	3.5×10^9 (N/m^2)
Poisson's ratio	0.3
Mass density	1340 (kg/m^3)
PZT 5H: Morgan Electroceramics	
Stiffness matrix	$\begin{bmatrix} 12.6 & 7.95 & 8.41 & 0 & 0 & 0 \\ 7.95 & 12.6 & 8.41 & 0 & 0 & 0 \\ 8.41 & 8.41 & 11.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.35 \end{bmatrix} \times 10^{10}$ (N/m^2)
Piezoelectric stress matrix	$\mathrm{e} = \begin{bmatrix} 0 & 0 & 0 & 0 & 17 & 0 \\ 0 & 0 & 0 & 17 & 0 & 0 \\ -6.55 & -6.55 & 23.3 & 0 & 0 & 0 \end{bmatrix}$ (F/m^2)
Relative dielectric matrix	$\begin{bmatrix} 1700 & 0 & 0 \\ 0 & 1700 & 0 \\ 0 & 0 & 1470 \end{bmatrix}$ (C/m^2)
Mechanical loss factor	65
Mass density	7500 (kg/m^3)

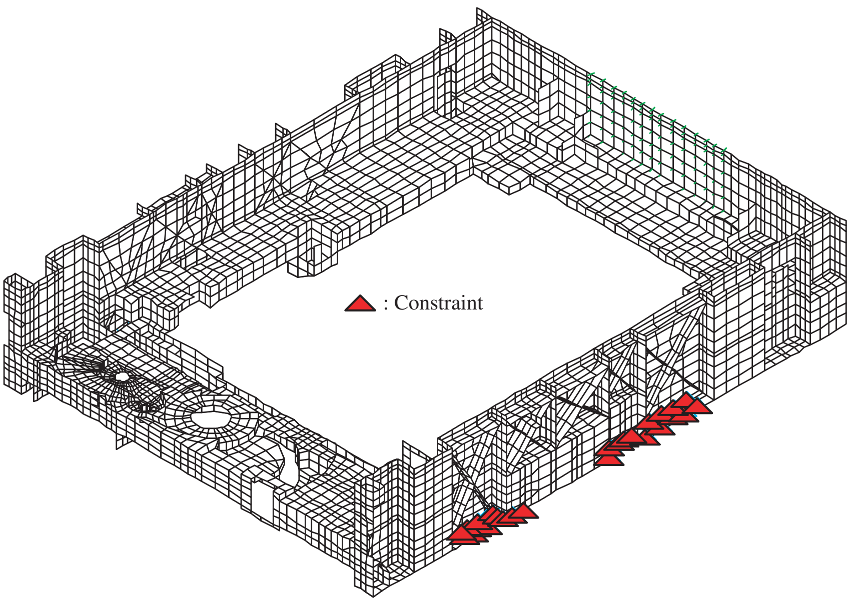

Fig. 2. Finite element model of the CD-ROM drive base.

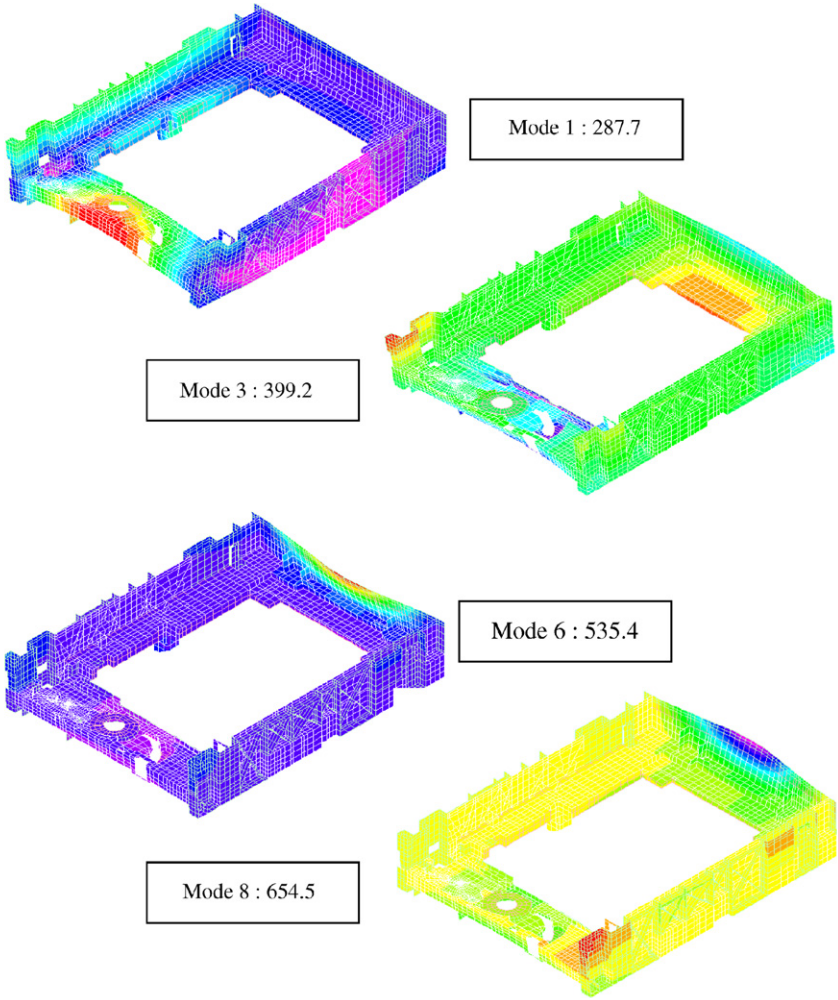

Fig. 3. Selected finite element modal analysis results of the drive base.

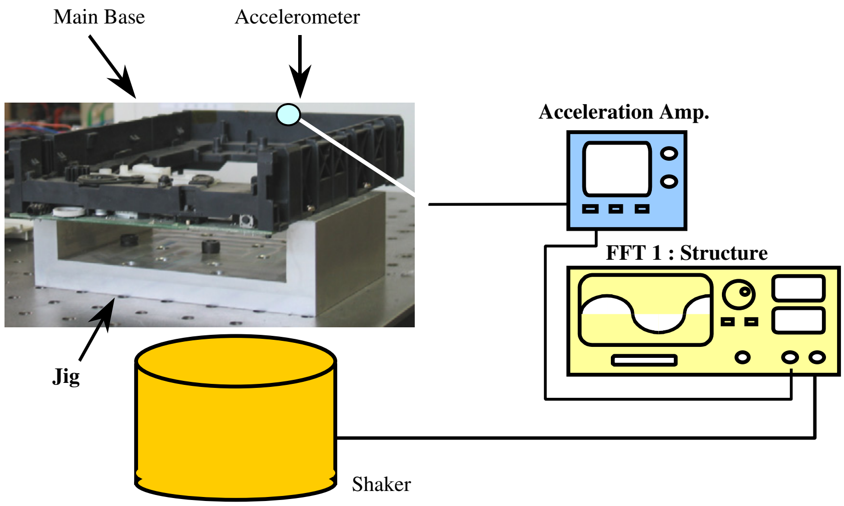

Fig. 4. Schematic diagram of the modal experimental apparatus.

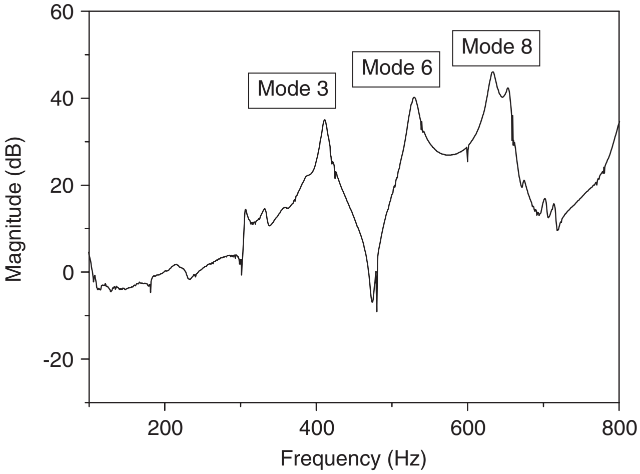

Fig. 5. Experimental frequency response of the drive base.

Table 2
Natural frequencies between FE modal analysis and experimental results

Mode	Finite element method Frequency (Hz)	Experiment Frequency (Hz)
3	399.2	411.9
6	535.4	529.3
8	654.5	634.7

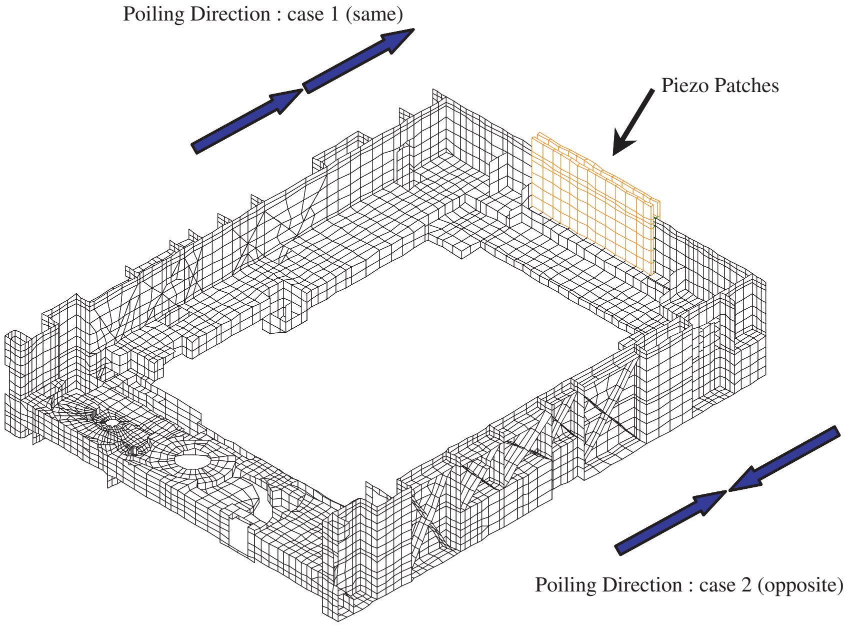

Fig. 6. Finite element model of the drive base with piezoelectric patches.

to shunt circuit, V_{cir}, and current flowing in the shunt circuit, I_{cir}, are expressed as follows:

$$V_{\mathrm{cir}} = V_O Y_{sp} \frac{Z_p Z_{\mathrm{cir}}}{Z_p + Z_{\mathrm{cir}}}, \tag{4}$$

$$I_{\mathrm{cir}} = \frac{Z_p}{Z_p + Z_{\mathrm{cir}}} I_O. \tag{5}$$

Then, the energy dissipated in the resistance of resonant shunt circuit, P_D, can be expressed as follows:

$$\begin{aligned} P_D &= \frac{1}{2}\left|V_{\mathrm{cir}}^R I_{\mathrm{cir}}^*\right| = \frac{1}{2}\left|(\mathrm{Re}(Z_{\mathrm{cir}})I_{\mathrm{cir}})I_{\mathrm{cir}}^*\right| \\ &= \frac{1}{2}\mathrm{Re}(Z_{\mathrm{cir}})|I_{\mathrm{cir}}|^2 \\ &= \frac{1}{2}\mathrm{Re}(Z_{\mathrm{cir}})\left|\frac{Z_p}{Z_p + Z_{\mathrm{cir}}}\right|^2 |I_O|^2 \\ &= \frac{1}{2}\mathrm{Re}(Z_{\mathrm{cir}})\left|\frac{Z_p}{Z_p + Z_{\mathrm{cir}}}\right|^2 |V_O|^2 \left|Y_{sp}\right|^2, \end{aligned} \tag{6}$$

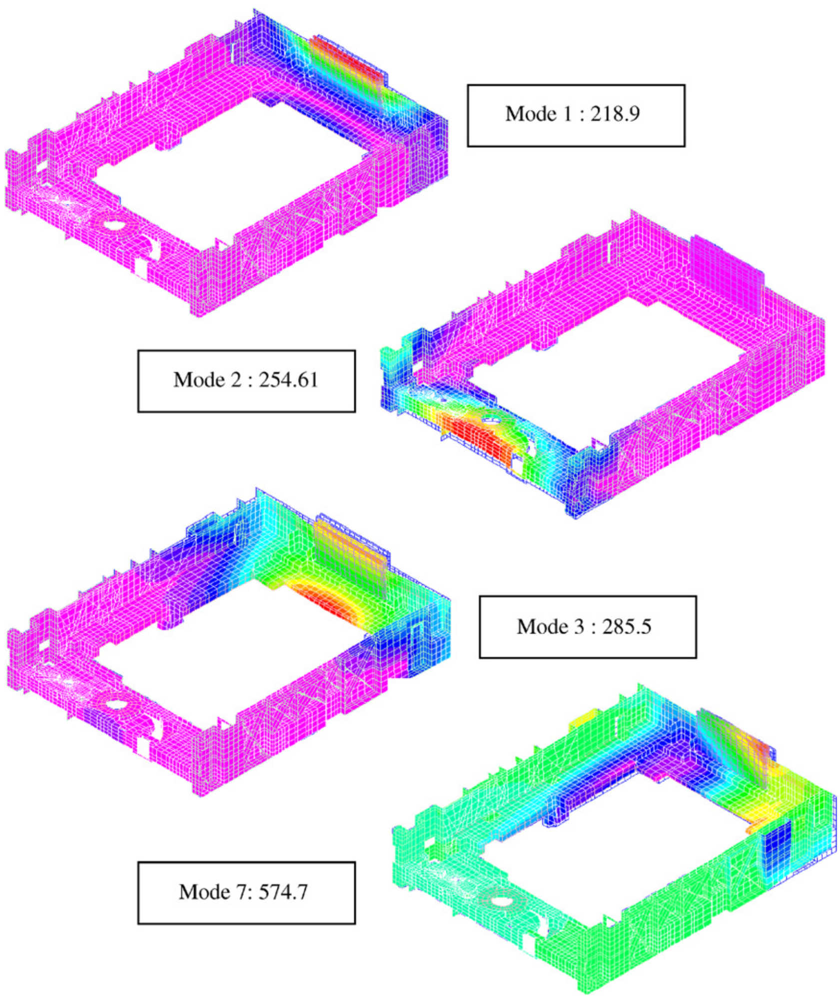

Fig. 7. Selected finite element modal analysis results of the drive base with piezoelectric patches.

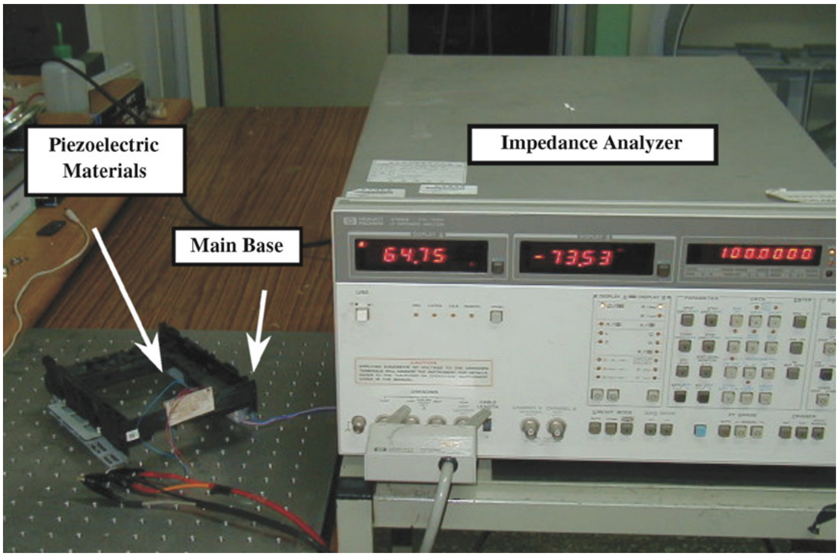

Fig. 8. Experimental apparatus for measuring admittance of drive base with piezoelectric patches.

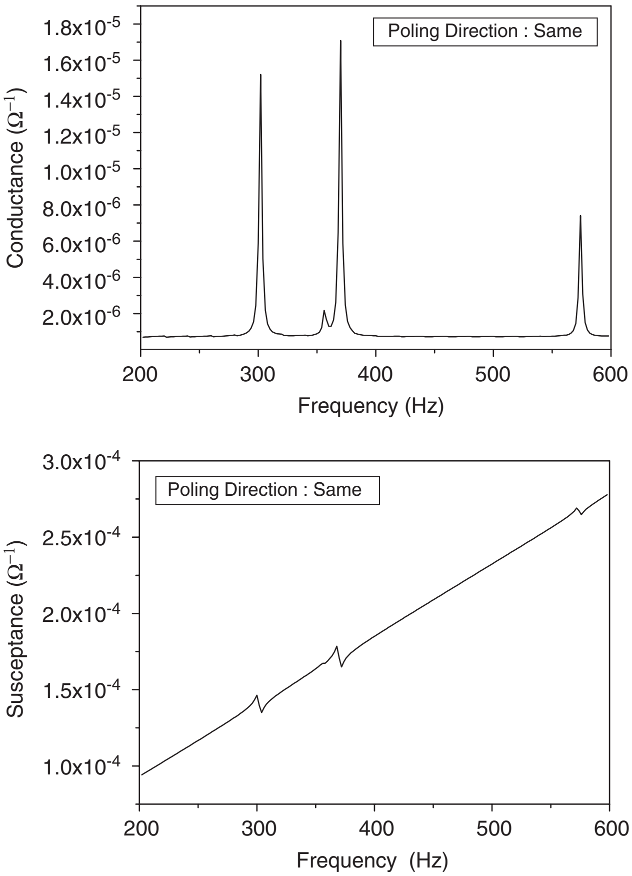

Fig. 9. Admittance—FEM analysis results of the drive base for the same poling direction (case 1).

where V_{cir}^{R} is the voltage applied at both end of resonant shunt circuit and I_{cir}^{*} is complex conjugate of the current in the shunt circuit. In Eq. (6), it is observed that the dissipated energy is proportional to the electro-mechanical characteristic values (I_O or $V_O\ Y_{sp}$) of piezoelectric structure in open circuit. In most cases, admittance of piezoelectric structure in open circuit can be measured using impedance analyzer by applying constant voltage with corresponding frequency on the piezoelectric material mounted on the structure. Therefore, the voltage, V_O, in Eqs. (2) and (6) represent the applied voltage to measure admittance and is independent constant from frequency. Then, the dissipated energy is only a function of admittance of piezoelectric structure in open circuit. This implies that the reduction of vibration in the piezoelectric shunt system is dependent on admittance of piezoelectric structure and admittance can be a performance index in designing piezoelectric structure.

Admittance of the piezoelectric structure is not only a key parameter of dissipated energy in the shunt system but also can represent system response of external excitation as follows [9]:

$$|Y| = |Z|^{-1} = \left|\frac{v}{F}\right| = T_f, \qquad |Y| = \sqrt{G^2 + B^2}, \tag{7}$$

where $Y = G + jB$, G: conductance, B: susceptance; Z, V, I: impedance, voltage, current—electrical part; v, F, T_f: velocity, force, transfer function—mechanical part.

The above equation represents the transfer characteristics of piezoelectric structure between the external excitation and system response. Therefore, the analysis of admittance can provide not only performance index but also design parameter of piezoelectric structure and system response.

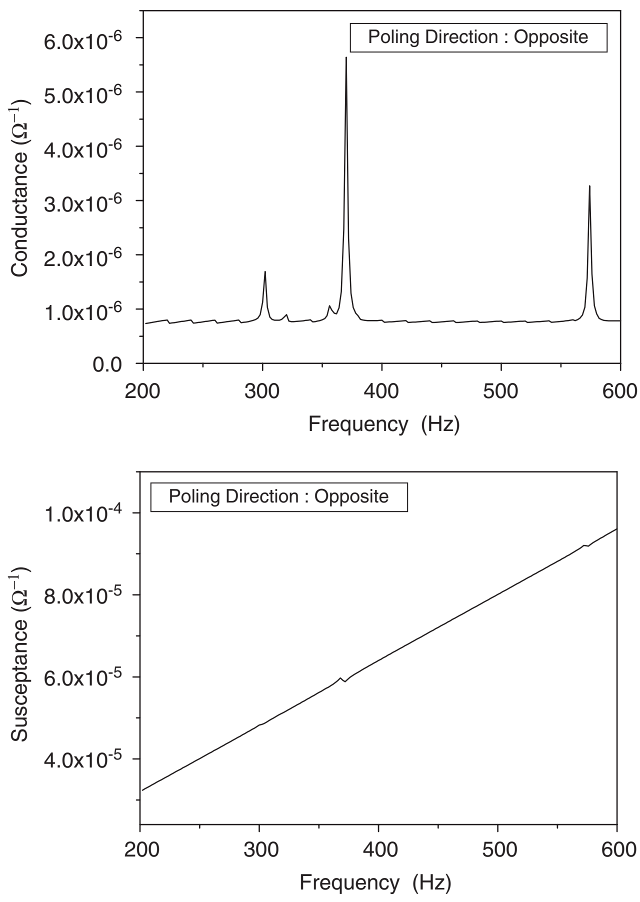

Fig. 10. Admittance—FEM analysis results of the drive base for the opposite poling direction (case 2).

The dynamic response and admittance of the complicated CD-ROM drive base are obtained using commercial finite element code, ANSYS. The equations of motion and admittance of the piezoelectric structure after finite element discretization can be expressed as follows [11]:

$$\begin{Bmatrix} [M] & [0] \\ [0] & [0] \end{Bmatrix} \begin{Bmatrix} [\ddot{u}] \\ [\ddot{\phi}] \end{Bmatrix} + \begin{Bmatrix} [D] & [0] \\ [0] & [0] \end{Bmatrix} \begin{Bmatrix} [\dot{u}] \\ [\dot{\phi}] \end{Bmatrix} + \begin{Bmatrix} [K] & [K_{u\phi}] \\ [K_{u\phi}]^{\mathrm{t}} & [K_{\phi}] \end{Bmatrix} \begin{Bmatrix} [u] \\ [\phi] \end{Bmatrix} = \begin{Bmatrix} [F] \\ [Q] \end{Bmatrix}, \quad (8)$$

$$|Y| = \left|\frac{I}{V}\right|, \quad I = j\omega \sum_i Q_i, \quad (9)$$

where $[F]$, $[u]$: vector of nodal structural forces and mechanical displacements; $[M]$, $[D]$, $[K]$: structural mass, damping and stiffness matrix; $[Q]$, $[\phi]$: vector of nodal electrical charges and potential; $[K_{u\phi}]$, $[K_{\phi}]$: piezoelectric coupling and dielectric conductivity matrix; "t": transposed; Q_i: the point charge of the ith node on the electrode.

From the above equations, mode shapes and natural frequencies of CD-ROM drive base with and without piezoelectric materials are analyzed and admittance of piezoelectric structure is obtained.

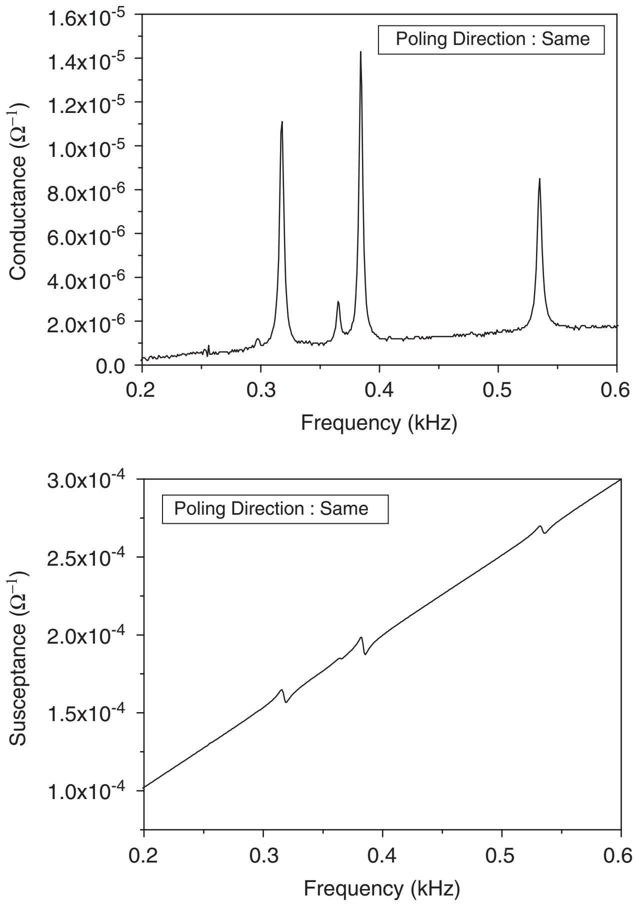

Fig. 11. Admittance—experimental measurement of the drive base for the same poling direction (case 1).

3. CD-ROM drive base with piezoelectric shunt circuit

3.1. Dynamic characteristics of CD-ROM drive base

First of all, modal analysis is conducted to investigate the dynamic characteristics of CD-ROM drive base without piezoelectric patches. Drive base is a complex structure consisting of stiffened rib, boss and hole as

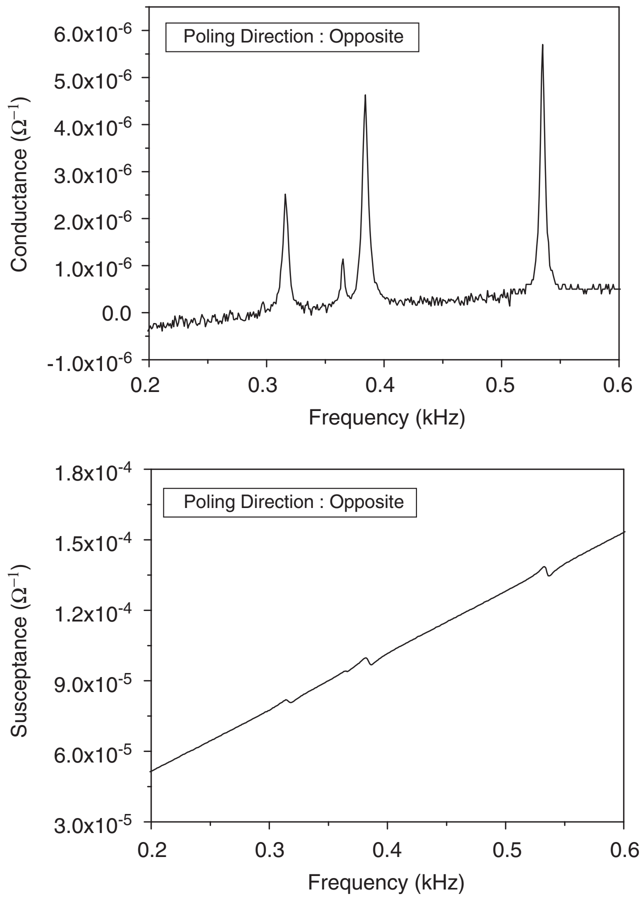

Fig. 12. Admittance—experimental measurement of the drive base for the opposite poling direction (case 2).

Table 3
Admittance comparison between FEM and experiment by poling direction

Poling direction	Experiment		Finite element method	
	Frequency (Hz)	Admittance $\lvert Y\rvert = \sqrt{G^2 + jB^2}$	Frequency (Hz)	Admittance $\lvert Y\rvert = \sqrt{G^2 + jB^2}$
Case 1	316	1.66E–04 (Ω^{-1})	300	1.47E–04 (Ω^{-1})
	383	2.00E–04 (Ω^{-1})	368	1.78E–04 (Ω^{-1})
	533	2.73E–04 (Ω^{-1})	572	2.69E–04 (Ω^{-1})
Case 2	314	8.19E–05 (Ω^{-1})	300	4.81E–05 (Ω^{-1})
	382	9.98E–05 (Ω^{-1})	368	5.97E–05 (Ω^{-1})
	533	1.39E–04 (Ω^{-1})	572	9.20E–05 (Ω^{-1})

shown in Fig. 1(a). The length, width and height of drive base proposed in the present study are 180, 140 and 40 mm, respectively. The drive base is made of ABS/PBT alloy and material properties are given in Table 1. Finite element model of drive base is given in Fig. 2. Four-node shell element is used in the present model. Total numbers of elements and nodes are 6797 and 7009, respectively. The drive base is fixed at the mid-bottom line as shown in Fig. 2.

Four representative mode shapes and corresponding natural frequencies are presented in Fig. 3. It is observed that large displacement has been occurred at the front part of drive base in the first mode. On the other hand, rear part of the drive base shows large displacement in the 3rd, 6th and 8th modes. It is hard to attach piezo patches at the front part of the drive base due to the complex geometry. In addition, disk loading motor and other PCB are installed at the front part when CD-ROM is assembled. Therefore, the stiffness of this part is increased after assembling of CD-ROM. In this section, the objective is to suppress vibration of rear part of CD-ROM where is easy to attach piezo patches and shows small change of stiffness after assembling of CD-ROM.

To verify numerical analysis, experimental apparatus is constructed as shown in Fig. 4. The drive base is fixed on the vibration isolation table by jig. Accelerometer is attached on the rear part of the drive base and frequency response is obtained by dynamic signal analyzer. Fig. 5 shows the obtained frequency response of the drive base. The corresponding natural frequency comparisons between numerical and experimental results are presented in Table 2. It is observed that the maximum relative difference between the numerical and experimental results is 3% and one can find that numerical model predicts well the dynamic characteristics of the drive base.

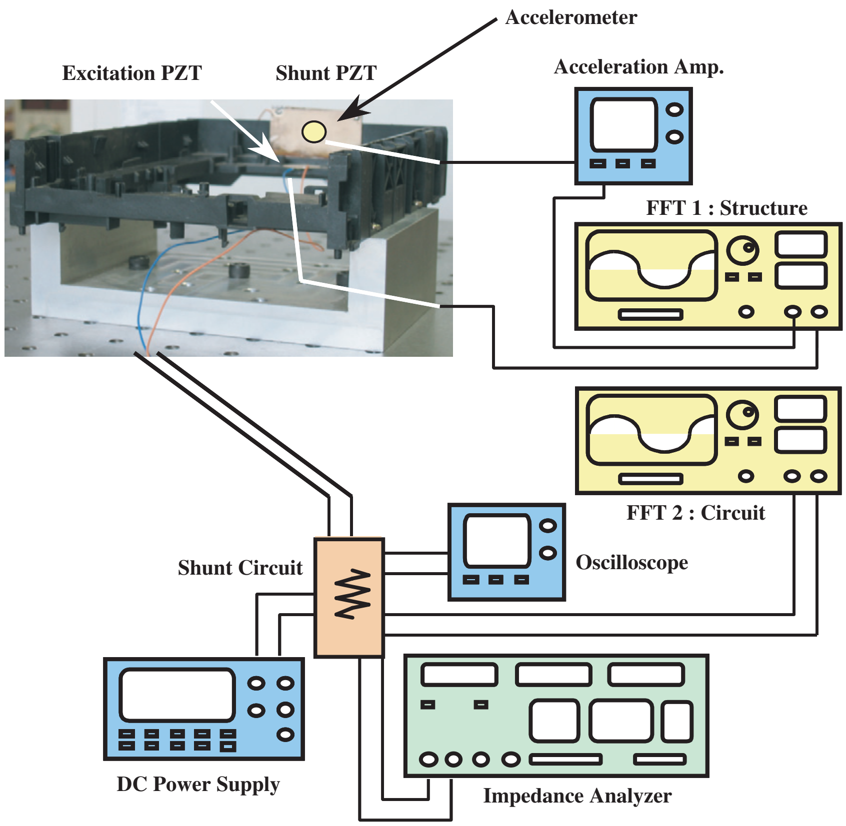

Fig. 13. Schematic diagram of the drive base shunt performance test apparatus.

3.2. Admittance analysis of CD-ROM drive base with piezoelectric patches

Based on the modal analysis results, carefully selected piezo patches are incorporated to the rear part of the drive base. The attached piezo patches are PZT 5H. The length, width and thickness are 50, 25 and 1 mm, respectively. Material properties of PZT 5H are given in Table 1. To improve the performance of piezoelectric shunt, two piezo pairs are attached at the front and back of the rear part of the drive base as shown in Fig. 6, which is the finite element model used in the present study. Now, modal analysis is conducted again to investigate the dynamic characteristics of drive base with piezo patches. Four representative mode shapes and corresponding natural frequencies are presented in Fig. 7. Since drive base is made of polymeric plastic which has low mass density and stiffness, the mode shapes and natural frequencies of the drive base with piezo patches show large differences from those of the original drive base due to the mass and stiffness of piezo patches. The 3rd and 6th modes of the original drive base, which are the major mode shapes of the rear part of the drive base, are changed to 1st and 3rd modes due to the piezo effects. The first mode shape of the original drive base is changed to the 2nd mode shape in the present model. The original 8th mode is changed to 7th mode with the natural frequency reduction of 80 Hz. The natural frequencies are decreased due to the mass effect of piezo patches and especially the natural frequency corresponding to the mode shapes related the rear part of the drive base is reduced to maximum 170 Hz.

Next, admittance analysis is conducted to investigate electro-mechanical coupling effect of the piezoelectric system and to predict piezoelectric shunt performance of the drive base. Since the performance of piezoelectric

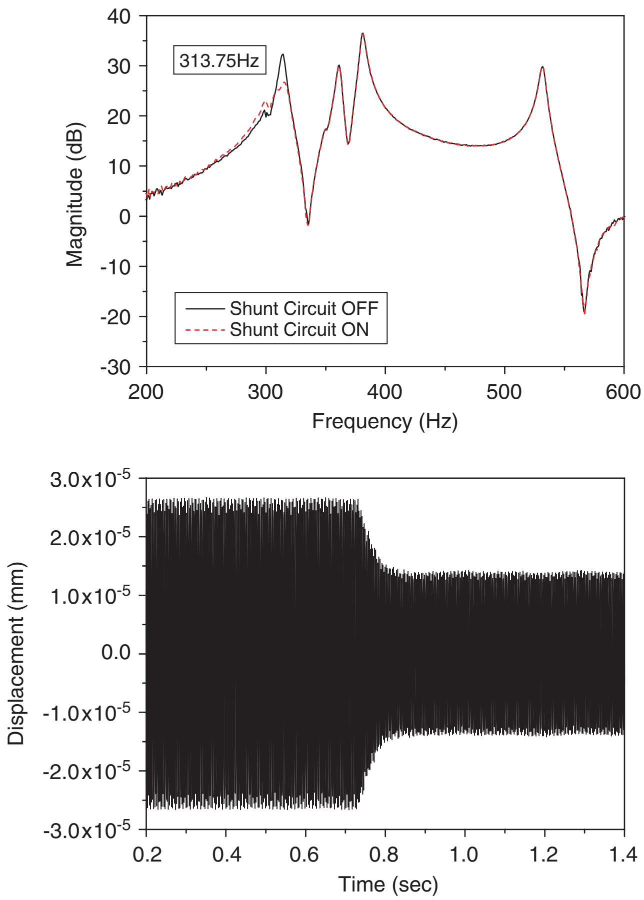

Fig. 14. Frequency and time responses of piezoelectric shunt damping at mode 1.

shunt damping is affected by the poling directions in case of multiple piezo patches, two different poling directions are considered as shown in Fig. 6. Experimental admittance is obtained by impedance analyzer as shown in Fig. 8. To measure admittance in the exciting frequency range, constant excitation voltage ($V_O = 1.1\,\mathrm{V}$) is applied to the piezo patches and frequency is swept from 200 to 600 Hz. The step size of sweeping frequency is 1 Hz. In numerical admittance analysis, charge for each node of electrode is obtained from the harmonic analysis of the equations of motion (Eq. (8)) under the same excitation voltage and frequency rage. Then, admittance of CD-ROM drive base with piezo patches is calculated based on the obtained charge of each electrode as shown in Eq. (9). Admittance consists of real and imaginary parts, which are called as conductance and susceptance. Therefore, admittance is analyzed by the variation of conductance and susceptance. Figs. 9 and 10 present numerical analysis results of admittance for two different poling directions. The experimentally measured admittances are given in Figs. 11 and 12. The frequencies and admittances at the peaks of conductance are listed in Table 3. It is clearly observed that the magnitude of admittance in case of opposite poling direction (case 2) is much smaller than that of the same poling direction (case 1). This represents that the vibration suppression of piezoelectric shunt is small in case of opposite poling direction. In case of same poling direction, the admittance obtained by numerical simulation correlates well with that obtained by experiment. The relative differences between experimental and numerical frequencies are 5%, 3.9% and 7.3%, respectively. The differences of peak admittance values are 11%, 11% and 1.5%, respectively. From these results, it is expected that piezoelectric shunt will suppress vibration of the drive base at the three peaks of admittance.

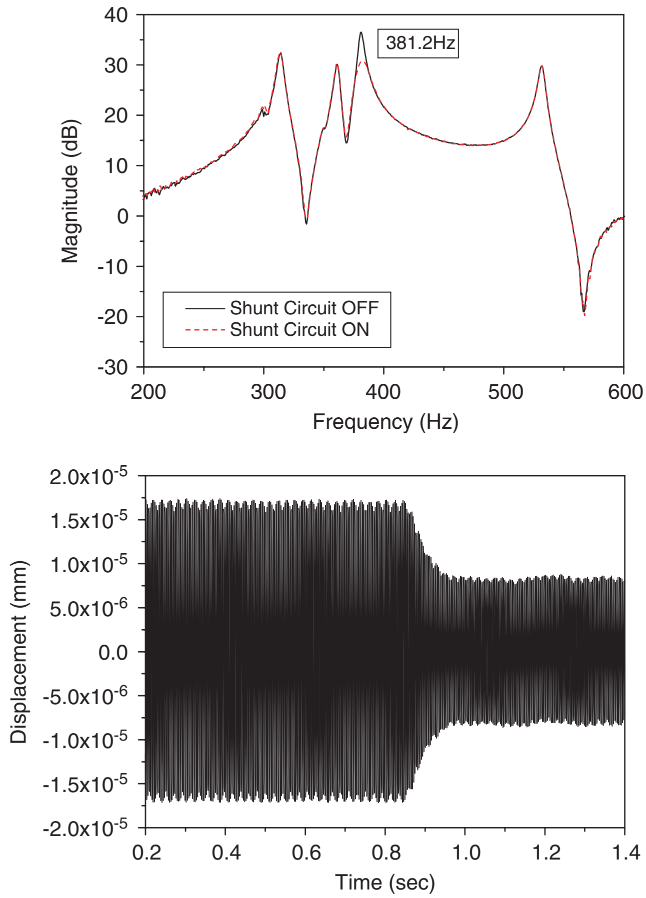

Fig. 15. Frequency and time responses of piezoelectric shunt damping at mode 3.

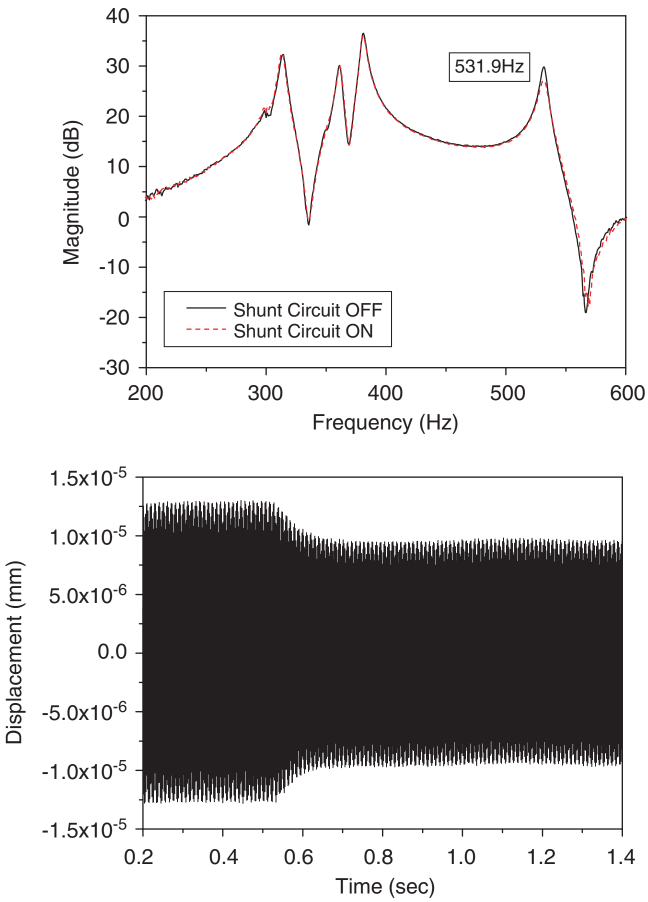

Fig. 16. Frequency and time responses of piezoelectric shunt damping at mode 7.

3.3. Shunt performance of the drive base

The poling direction and target piezoelectric shunt frequencies are obtained by admittance analysis. Now, piezoelectric shunt damping is measured for the same poling direction (case 1). Experimental apparatus for measuring frequency and time response of CD-ROM drive base with piezo patches is presented in Fig. 13. Resonant shunt circuit is connected to the piezo patches and tuned resistor (R_{cir}) and inductance (L_{cir}) to suppress the vibration of each target mode. Synthetic inductor consisting of OP amps and resistor is used in the resonant shunt circuit and therefore, DC power supply is connected to the shunt circuit. Actuating PZT is attached to excite the CD-ROM drive base. Figs. 14–16 show the performance of piezoelectric shunt damping for the predicted three target frequencies in the frequency and time domains. It is clearly observed that the piezoelectric damping decrease the magnitude of frequency responses to 6, 6 and 3 dB in the predicted target modes. In first mode, the magnitude of vibration in time domain is reduced from 26.2 to 14.2 μm after shunt circuit on. Those of the 3rd and 7th modes are reduced from 17.1 to 8.1 μm and from 12.8 to 8.7 μm, respectively. One can find that 50 percent of amplitude reduction in vibration is achieved. When piezoelectric shunt damping test is conducted for the opposite poling direction (case 2), it was observed that there was very small piezoelectric damping effects. This concludes that admittance analysis can predict the performance of piezoelectric shunt damping.

4. Concluding remarks

The vibration suppression of CD-ROM drive base was investigated using piezoelectric shunt circuit. Admittance of piezoelectric structure was introduced to predict the performance of piezoelectric shunt damping. Modal analysis using finite element method and experimental modal test of CD-ROM drive base were conducted to analyze dynamic characteristics of CD-ROM drive base. After that, CD-ROM drive base was incorporated with piezoelectric patches and admittance analysis has been conducted to investigate electro-mechanical characteristics of the piezoelectric system. From the admittance analysis, target modes and frequencies were obtained and multimode piezoelectric shunt damping was realized with resonant shunt circuit. Experimental results proved that piezoelectric shunt damping is an effective approach to reduce undesirable vibration of the drive base. It is expected that vibration reduction by piezoelectric shunt damping will give a significant improvement of the performance of the CD-ROM drive. Finally, this study provides that admittance is capable of predicting the performance of piezoelectric shunt damping. However, the exact relation between admittance and the performance of piezoelectric shunt damping to predict damped system response is not realized. Therefore, it is remarked that the exact relation between admittance and the damped system response will be undertaken as a second phase of this study.

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References

[1] S.H. Chang, H.S. Kim, J.K. Choi, D.G. Lee, A study on the design of vibration damper for high speed CD-ROM drive, *Journal (A) of Korean Society Mechanical Engineering* 22 (1998) 939–952.
[2] N.W. Kim, K.W. Kim, G. Hong, M.C. Chung, W.Y. Kim, An anti-vibration design of a slim type optical disk drive, *Journal of Korean Society Noise and Vibration Engineering* 9 (1999) 324–330.
[3] J. Lee, W.K. Van Moorhen, Analytical and experimental analysis of a self-compensating dynamic balancer in a rotating mechanism, *ASME Journal of Dynamic System, Measurements, and Control* 118 (1996) 468–475.
[4] S.C. Lim, J.S. Park, S.B. Choi, Y.P. Park, Vibration control of a CD-ROM feeding system using electro-rheological mounts, *Journal of Intelligent Material Systems and Structures* 12 (2001) 629–637.
[5] J.S. Park, S.C. Lim, S.B. Choi, J.H. Kim, Y.P. Park, Vibration reduction of a CD-ROM drive base using a piezoelectric shunt circuit, *Journal of Sound and Vibration* 269 (2004) 1111–1118.
[6] N.W. Hagood, A. Von Flotow, Damping of structural vibrations with piezoelectric materials and passive electrical networks, *Journal of Sound and Vibration* 146 (1991) 243–268.
[7] H. Asheley, D.L. Edberg, On the virtues and prospects for passive damping in large space structures, *Air Force Damping Worksop II*, 1985.
[8] J.J. Hollkamp, Multimodal passive vibration suppression with piezoelectric materials and resonant shunts, *Journal of Intelligent Material Systems and Structures* 5 (1994) 49–57.
[9] J. Kim, Y.H. Ryu, S.B. Choi, New shunting parameter tuning method for piezoelectric damping based on measured electrical impedance, *Smart Materials and Systems* 9 (2000) 868–877.
[10] G.A. Lesieutre, Vibration damping and control using shunted piezoelectric materials, *The Shock and Vibration Digest* 30 (1998) 187–195.
[11] ANSYS INC., ANSYS Theory Manual Version 5.5, *SAS IP*, 1999.