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Isolation of vibrations due to speakers in audio-visual electronic devices without deteriorating vibration of speaker cone †

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Abstract

As audio-visual electronic devices such as TV and laptop computer get thinner, vibrations due to speakers bring about sometimes deteriorations in the audio-visual performance. When visco-elastic isolators are installed between speakers and device structures in order to reduce the structural vibration just based on the transmissibility of a single-degree of freedom system, other by-product problems may occur, such as the structural vibration noise inside the devices or the decrease of read/write speed in a hard disk drive system. In this paper, how to isolate speakers is presented so as to reduce the structural vibration of audio-visual electronic devices without reducing the vibration of the cone in speakers. An electro-mechanical vibration model for the whole system, which includes a loud speaker, vibration isolators and a device structure, is derived based on the substructure synthesis method. A dynamic model is derived mathematically for the loud speaker, isolators are treated as lumped springs and damping elements and the device structure is characterized experimentally in terms of compliance. Subsequently, they are coupled using frequency response functions at the connection points. It is claimed that, through simulations on modification of the isolator stiffness and loss factor, a realistically 'good' isolator can be designed before making a prototype so that the vibration of the structure may be the minimum, yet without reducing the key performance of a loud speaker in terms of vibration of speaker cone.

Keywords: Excitation by speaker; Isolation of speaker; Substructure synthesis; Structural vibration

1. Introduction

As audio-visual electronic devices are getting thinner, the forces due to a speaker operation in those devices cause some vibration problems, for example, the structural vibration in a thin-flat television and a drop of read/write speed in HDD of a laptop computer, etc. Such problems have recently been found by some companies and not been reported in any literature previously.

Most speakers are voice coil type, which are driven by the electric-magnetic force generated by a voice coil and a permanent magnet. This force moves the cone of speakers back and forth, and the cone makes sounds. Meanwhile, the electric-magnetic force also exerts on the frame of the device to which the speakers belong according to Newton's 3rd law and it makes the vibration of components in those devices. Even though isolators are installed between speakers and device frames, those vibration problems are not solved clearly in the field.

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In a thin LCD TV, there may exist two components having a small gap between them. When the speaker volume is small, the vibration makes no problem. However, if the volume becomes large, the collision between components brings about some structural vibration noise.

In this paper, the stiffness and loss factor of isolators are investigated to decrease the vibration on a TV frame without reducing the vibration of the cone in the speaker. The exciting frequency range by speakers is audible frequency range, which is from 20 to 20 kHz. In this range, a TV frame shows many elastic modes, so it is very hard to model the system (speaker and TV frame) with rigid bodies and springs. In other words, a model with a few degrees of freedom cannot describe the dynamics of a TV frame sufficiently. Therefore, the substructure synthesis method is introduced to establish the model in this study. Compliances of a TV frame were obtained through experiments and a speaker model was derived mathematically, then a model for the whole system was obtained using the FRF coupling technique. Finally, through simulations, the stiffness of isolators was investigated to reduce the vibration of the TV frame without deteriorating the vibration of the speaker cone.

2. Substructure synthesis for a TV

To eliminate the structural vibration noise, the vibration of a TV frame should be decreased without reducing the vibration of the speaker cone. For this purpose, we decided to change the stiffness and loss factor of isolators between a speaker and a TV frame. To see the effects of the stiffness and loss factor, a dynamic model for a TV including a speaker is needed.

The exciting frequency range by a speaker is audible frequency range, which is from 20 to 20 kHz. In this range, a TV frame shows many elastic modes, so it is very hard to model the system (speaker and TV frame) with rigid bodies and springs. Therefore, the substructure synthesis method is introduced to establish the model in this study. Compliances of a TV frame were obtained through experiments and a speaker model was derived mathematically, then the model for the whole system was obtained using the FRF coupling technique.

The system under study consists of a TV frame and a speaker as shown in Fig. 1(a), where the size of the speaker has been magnified relative to the TV frame for an easier illustration. The system is shown schematically in Fig. 1(b), i.e, a bobbin and a cone on the speaker frame, which is to be isolated from the TV frame. An electric circuit appears in Fig. 1(c) and three substructures are shown in Fig. 1(d); a speaker, isolators, and a TV frame.

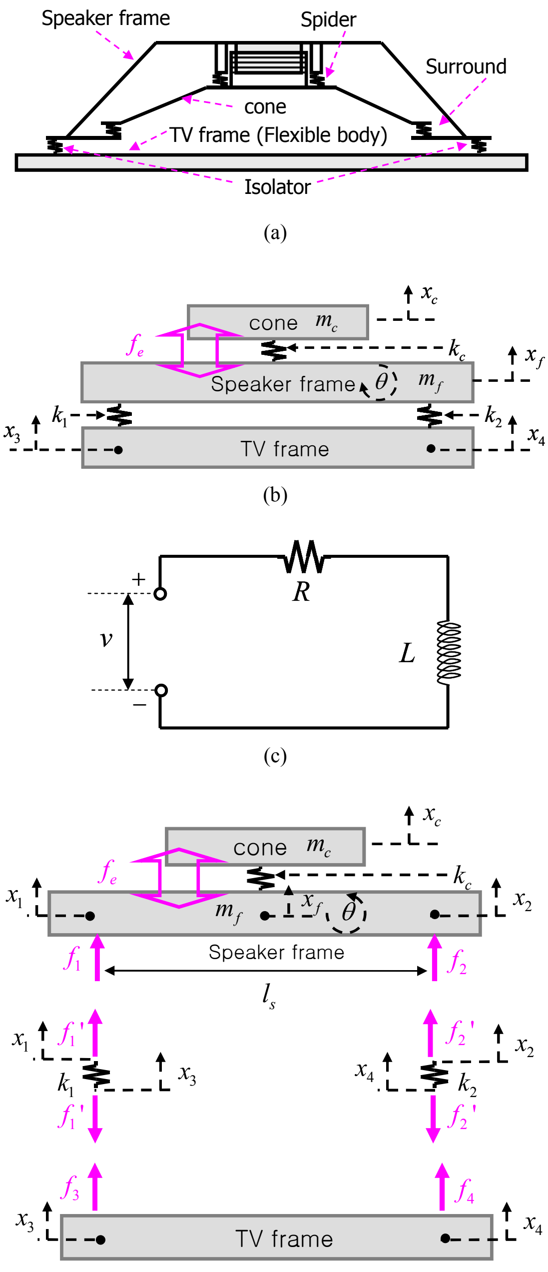

Fig. 1. Construction of a TV system: (a) Shape of a speaker attached to a TV frame; (b) Schematic diagram for the whole system; (c) The electric circuit inside the speaker; (d) Three subsystems.

2.1 Substructure models

2.1.1 Speaker

A speaker is modelled as a 4 degrees of freedom electromechanical system; translational and rotational motion of the speaker frame, motion of the bobbin and the current in the voice coil. The inputs are the voltage to the coil and forces f_1, f_2 at two points of connection onto isolators, as shown in Figs. 1(c) and (d). Governing equations are:

$$L\dot{i} + Ri = v - Bl_w(\dot{x}_c - \dot{x}_f) \tag{1}$$

$$m_c\ddot{x}_c + c_c(\dot{x}_c - \dot{x}_f) + k_c(x_c - x_f) = f_e = Bl_w i \tag{2}$$

$$\begin{aligned} &m_f\ddot{x}_f + c_c(\dot{x}_f - \dot{x}_c) + k_c(x_f - x_c) \\ &\quad = -f_e + f_1 + f_2 = -Bl_w i + f_1 + f_2 \end{aligned} \tag{3}$$

$$I_f\ddot{\theta} = \frac{l_s}{2}(f_2 - f_1)\,. \tag{4}$$

Eq. (1) is the governing equation for the electric circuit, where L is the inductance of the coil, R resistance, i current, v voltage, B magnetic flux density, l_w length of the coil, x_c, x_f translational displacement of cone and speaker frame respectively. In the electric circuit, the counter electromotive force occurs in proportion to the relative velocity of the cone and the speaker frame [1].

Eq. (2) is for the motion of the cone and bobbin, where m_c is the mass of the cone and bobbin, k_c, c_c stiffness and damping coefficient of the spider and surround springs, f_e electromagnetic force equal to the product of the current, magnetic flux density and length of the coil. It is noted that the electromagnetic force acts between the bobbin and speaker frame and, hence, also appears as a reaction force in Eq. (3) which is for the motion of the speaker frame. Eq. (4) is for the rotational motion of the speaker frame, where I_f denotes the moment of inertia, θ rotational displacement, l_s distance between two isolators.

By Fourier transforming Eqs. (1)-(4), transfer function matrix between the electromechanical inputs and outputs can be obtained as below.

$$\begin{Bmatrix} I \\ X_c \\ X_1 \\ X_2 \end{Bmatrix} = \begin{bmatrix} {}_SH_{11} & {}_SH_{12} & {}_SH_{13} \\ {}_SH_{21} & {}_SH_{22} & {}_SH_{23} \\ {}_SH_{31} & {}_SH_{32} & {}_SH_{33} \\ {}_SH_{41} & {}_SH_{42} & {}_SH_{43} \end{bmatrix} \begin{Bmatrix} V \\ F_1 \\ F_2 \end{Bmatrix} \tag{5}$$

where each element is formulated as follows:

$${}_SH_{11} = \frac{j\omega h}{h(jR\omega - L\omega^2) - B^2 l_w{}^2 \omega^2 (m_c + m_f)} \tag{5a}$$

$${}_SH_{12} = {}_SH_{13} = \frac{j\omega B l_w m_c}{h(jR\omega - L\omega^2) - B^2 l_w{}^2 \omega^2 (m_c + m_f)} \tag{5b}$$

$${}_SH_{21} = \frac{m_f B l_w}{h(jL\omega + R) + jB^2 l_w{}^2 \omega (m_c + m_f)} \tag{5c}$$

$${}_SH_{22} = {}_SH_{23}$$
$$= \frac{j\omega m_c m_f B^2 l_w{}^2}{h^2 (j\omega L + R) + jB^2 l_w{}^2 \omega (m_c + m_f)} - \frac{jd_c + k_c}{h\omega^2} \tag{5d}$$

$${}_SH_{31} = -\frac{m_c B l_w}{h(jL\omega + R) + jB^2 l_w{}^2 \omega (m_c + m_f)} \tag{5e}$$

$${}_SH_{32} = \frac{m_c\omega^2 - k_c - jd_c}{\omega^2 h}$$
$$- \frac{j\omega m_c m_f B^2 l_w{}^2}{h^2 (j\omega L + R) + jB^2 l_w{}^2 \omega (m_c + m_f)} - \frac{l_s{}^2}{4\omega^2 I_f} \tag{5f}$$

$${}_SH_{33} = \frac{m_c\omega^2 - k_c - jd_c}{\omega^2 h}$$
$$- \frac{j\omega m_c m_f B^2 l_w{}^2}{h^2 (j\omega L + R) + jB^2 l_w{}^2 \omega (m_c + m_f)} + \frac{l_s{}^2}{4\omega^2 I_f} \tag{5g}$$

$${}_SH_{41} = -\frac{m_c B l_w}{h(jL\omega + R) + jB^2 l_w{}^2 \omega (m_c + m_f)} \tag{5h}$$

$${}_SH_{42} = \frac{m_c\omega^2 - k_c - jd_c}{\omega^2 h}$$
$$- \frac{j\omega m_c m_f B^2 l_w{}^2}{h^2 (j\omega L + R) + jB^2 l_w{}^2 \omega (m_c + m_f)} + \frac{l_s{}^2}{4\omega^2 I_f} \tag{5i}$$

$${}_SH_{43} = \frac{m_c\omega^2 - k_c - jd_c}{\omega^2 h}$$
$$- \frac{j\omega m_c m_f B^2 l_w{}^2}{h^2 (j\omega L + R) + jB^2 l_w{}^2 \omega (m_c + m_f)} - \frac{l_s{}^2}{4\omega^2 I_f}. \tag{5j}$$

Translational and rotational displacements of speaker frame x_f and θ have been replaced with x_1 and x_2 which are translational displacements at the connection points with isolators as shown in Fig. 1(d). Their relations can be expressed by $x_1 = x_f - \theta l_s / 2$ and $x_2 = x_f + \theta l_s / 2$. Also, a hysteretic damping coefficient d_c has been used instead of the viscous damping c_c and h defined below has been introduced to simplify the equation.

$$h = -m_c m_f \omega^2 + k_c (m_c + m_f) + jd_c (m_c + m_f) \tag{6}$$

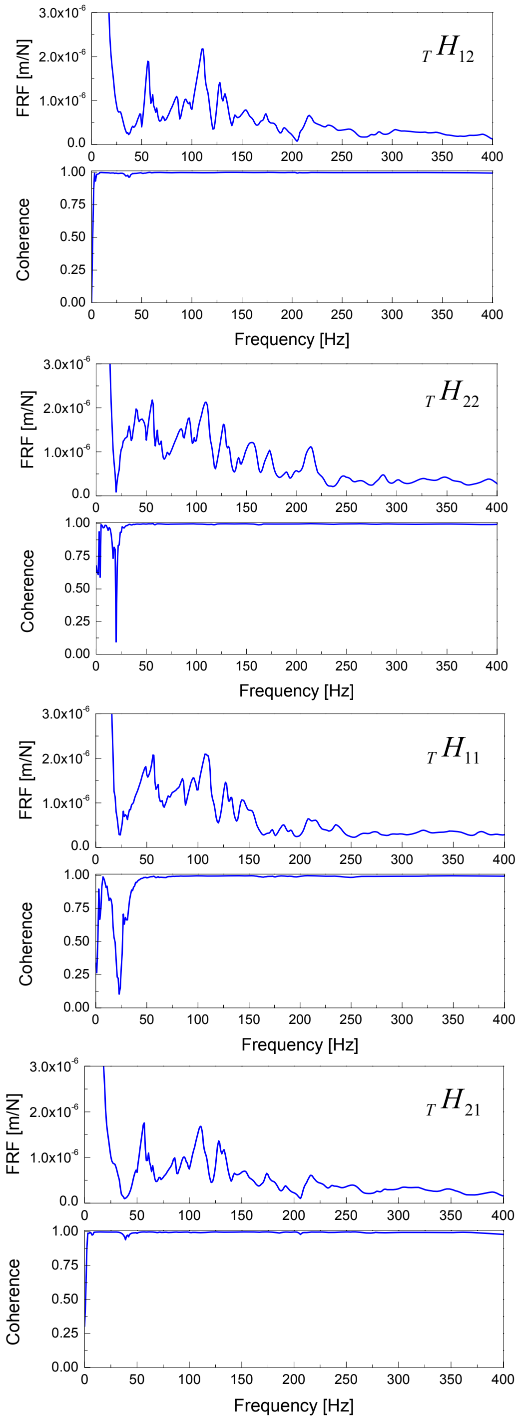

Fig. 2. Compliance of a TV frame.

The parameters for the speaker components such as the magnetic flux density, stiffness and damping of spider and surround springs were obtained experimentally [2].

2.1.2 TV frame

The compliances of a TV frame were formulated at two points of the isolators as in Eq. (7), and obtained from an impact test. The measurements are shown in Fig. 2.

$$\begin{Bmatrix} X_3 \\ X_4 \end{Bmatrix} = \begin{bmatrix} {}_T H_{11} & {}_T H_{12} \\ {}_T H_{21} & {}_T H_{22} \end{bmatrix} \begin{Bmatrix} F_3 \\ F_4 \end{Bmatrix} \tag{7}$$

2.1.3 Isolators

For the stiffness of isolators, which is the design variable, Eq. (8) is used.

$$\begin{Bmatrix} F_1' \\ F_2' \end{Bmatrix} = \begin{bmatrix} k_1^* & 0 \\ 0 & k_2^* \end{bmatrix} \begin{Bmatrix} X_1 - X_3 \\ X_2 - X_4 \end{Bmatrix} \tag{8}$$

where k_1^*, k_2^* denote complex stiffness of isolators.

2.2 Synthesis

The governing Eqs. (5), (7) and (8) of three subsystems, i.e., the speaker, TV frame and isolators respectively can be rewritten as below.

$$\begin{Bmatrix} {}_S\mathbf{x}_u \\ {}_S\mathbf{x}_i \end{Bmatrix} = \begin{bmatrix} {}_S \overset{2\times1}{H}_{uv} & {}_S \overset{2\times2}{H}_{uf} \\ {}_S \overset{2\times1}{H}_{iv} & {}_S \overset{2\times2}{H}_{if} \end{bmatrix} \begin{Bmatrix} V \\ {}_S\mathbf{F}_i \end{Bmatrix} \tag{9}$$

$$\{{}_T\mathbf{x}_i\} = {}_T H \, {}_T\mathbf{F}_i \tag{10}$$

$$\{{}_I\mathbf{F}'\} = {}_I H \{{}_S\mathbf{x}_i - {}_T\mathbf{x}_i\} \tag{11}$$

where the left-subscripts represent each subsystem – S for speaker, I for isolator and T for TV – and the right-subscripts express characteristics of variables – i for connection to isolators and u for unconnection.

Applying the action-reaction law given as Eq. (12) to the forces in Eqs. (9) to (11) and combining them, Eq. (13) can be derived.

$$ {}_S\mathbf{F}_i = -{}_I\mathbf{F}', \quad {}_T\mathbf{F}_i = {}_I\mathbf{F}' \tag{12}$$

$$\begin{bmatrix} I & {}_S H_{uf\,I} H & -{}_S H_{uf\,I} H \\ 0 & I + {}_S H_{if\,I} H & -{}_S H_{if\,I} H \\ 0 & -{}_T H_{i\,I} H & I + {}_T H_{i\,I} H \end{bmatrix} \begin{Bmatrix} {}_S\mathbf{x}_u \\ {}_S\mathbf{x}_i \\ {}_T\mathbf{x}_i \end{Bmatrix} = \begin{bmatrix} {}_S H_{uv} \\ {}_S H_{iv} \\ 0 \end{bmatrix} V \tag{13}$$

Finally, by matrix inversion, we can get Eq. (14) for the predictions of responses of the whole system [3].

$$\begin{Bmatrix} {}_S\mathbf{x}_u \\ {}_S\mathbf{x}_i \\ {}_T\mathbf{x}_i \end{Bmatrix} = \{I \quad X_c \quad X_1 \quad X_2 \quad X_3 \quad X_4\}^T = \begin{bmatrix} I & {}_S H_{uf\,I} H & -{}_S H_{uf\,I} H \\ 0 & I + {}_S H_{if\,I} H & -{}_S H_{if\,I} H \\ 0 & -{}_T H_{i\,I} H & I + {}_T H_{i\,I} H \end{bmatrix}^{-1} \begin{bmatrix} {}_S H_{uv} \\ {}_S H_{iv} \\ 0 \end{bmatrix} V \tag{14}$$

That is, for a given voltage input, we can predict the current in the electric circuit I, displacement of the cone and bobbin X_c directly related to the sound, displacements of the speaker X_1 and X_2, and vibrations of the TV frame X_3 and X_4.

Table 1. Stiffness of three isolators.

Sample	Stiffness (k)	Loss factor (η)
#1	29.06 kN/m	0.1793
#2	55.72 kN/m	0.1772
#3	84.62 kN/m	0.0823

Table 2. Parameters for simulation.

Parameter	Value
Mass of cone	m_c=1.45X10^{-3}kg
Mass of speaker frame	m_f=72X10^{-3}kg
Moment of inertia of speaker frame	I_f=5.4718X10^{-4} $kg \cdot m^2$
Inductance of voice coil	L=2.6534X10^{-4}H
Resistance of voice coil	R=7.5 Ω
Height of voice coil	l_c=4X10^{-3}m
Length of voice coil	l_w=3.29m
Length between two points connected to isolators on speaker	l_s=0.15m
Stiffness of surround and spider	k_c=2.2216kN/m
Hysteretic damping coefficient of surround and spider	d_c=498.75 $N \cdot s^2 / m$
Magnetic flux density	B=0.134T

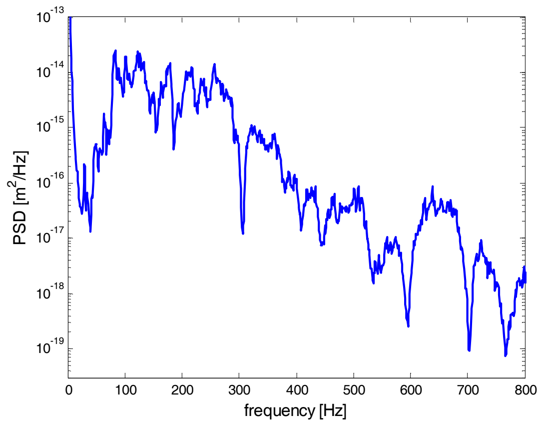

Fig. 3. Power spectral density of displacement on TV frame.

3. Simulations on the performance of isolators between a speaker and a TV

The effects of three commercially available isolators shown in Table 1 on the performance of a speaker and the vibration of a TV frame are investigated.

The vibration of a point on a TV frame was measured during speaker operations to decide the frequency range of interest. The power spectral density of the displacement rather than the velocity or acceleration is shown in Fig. 3. The reason is that, as explained in the introduction, the collision between components in a TV frame could occur when the displacement of a component relative to another exceeds a given limit. It can be seen that most significant vibrations show up below 400 Hz. Therefore, the upper limit of frequency was chosen as 400 Hz.

For three samples of isolators given in Table 1, the frequency response functions of the vibration velocity of the

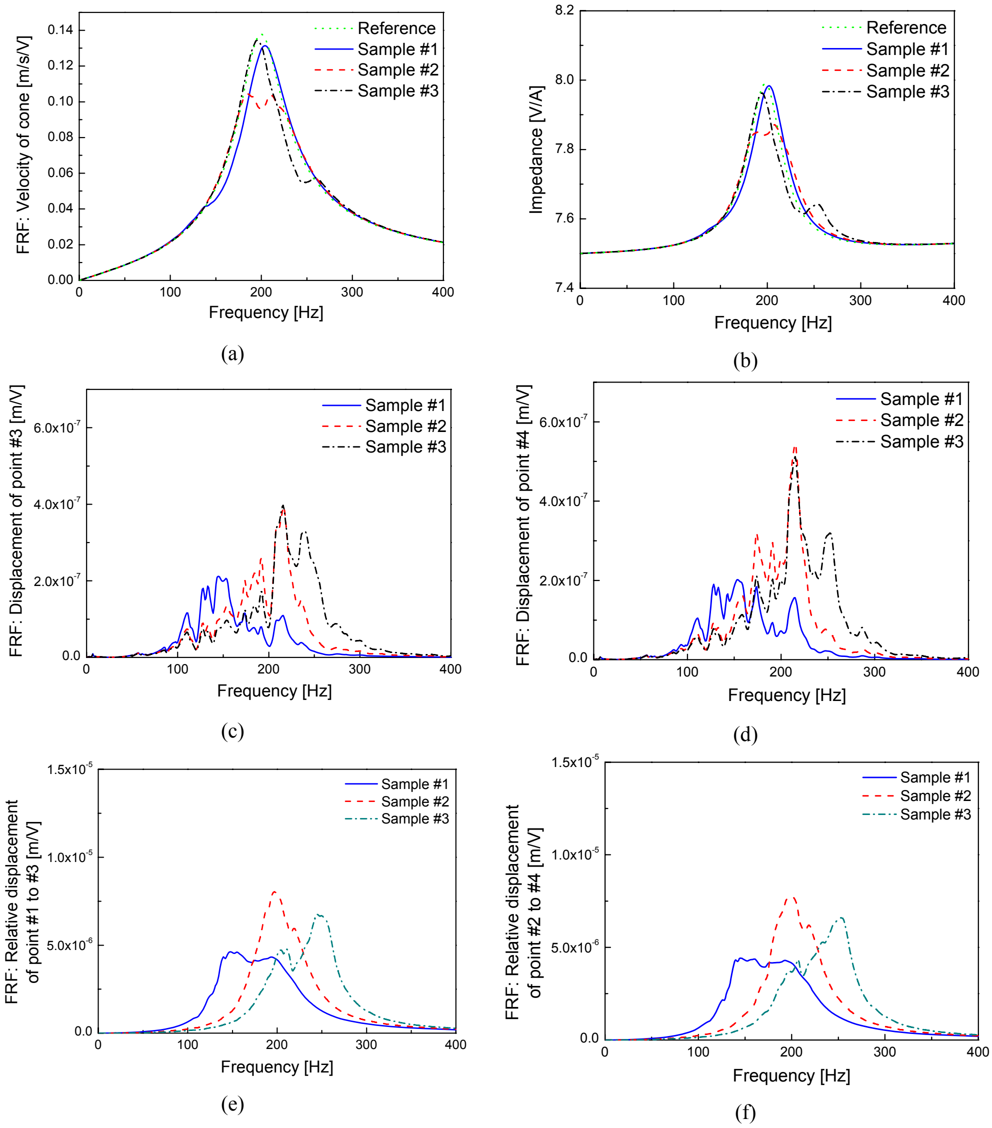

Fig. 4. System responses with respect to the voltage input with three sample isolators, FRF: (a) Velocity of cone; (b) Electric impedance; (c) Displacement of point #3 on TV frame; (d) Displacement of point #4 on TV frame; (e) Relative displacement of point #1 to #3; (f) Relative displacement of point #2 to #4.

speaker cone, impedance for the electric circuit, and vibration displacements of the TV frame, relative displacements of speaker to TV frame with respect to the electric voltage were calculated and shown in Fig. 4. For the numerical studies, the values in Table 2 were used. In Fig. 4(a), the reference model which is a speaker cone, having single degree of freedom, installed on a fixed frame is introduced for comparison of the cone motion. The reference model has a resonance at about 200 Hz and due to the change of isolator stiffness, the distortion on FRF curve is observed. As the stiffness goes smaller, the frequency where the distortion on FRF curve occurs goes to the lower frequency region. For sample #3 which is the largest stiffness among three, the distortion on FRF curve occurs at about 250 Hz, and for sample #2 and #1, the distortions are observed at about 200 Hz and 150 Hz, respectively. Meanwhile, the frequency region where the significant vibration occurs on the TV frame also goes to the lower frequency region as shown in Figs. 4(c) and (d). From the results explained above, it is concluded that using three sample isolators deteriorates the vibration of speaker cone.

For finding the stiffness of isolators to reduce the vibration on TV frame without deteriorating the vibration of the cone, the stiffness has been changed to 1/16, 1/8, 1/4, 4 and 8 times the stiffness for the second sample and its loss factor was fixed as same as the second sample. The results of the numerical studies are illustrated in Fig. 5. It is observed that the FRF for the cone motion does not change much from the reference model as shown in Fig. 5(a). Moreover, it is shown that the vibration on the TV frame has been greatly reduced with these stiffnesses, and it can be seen that the 1/16 and 1/8 time stiff-

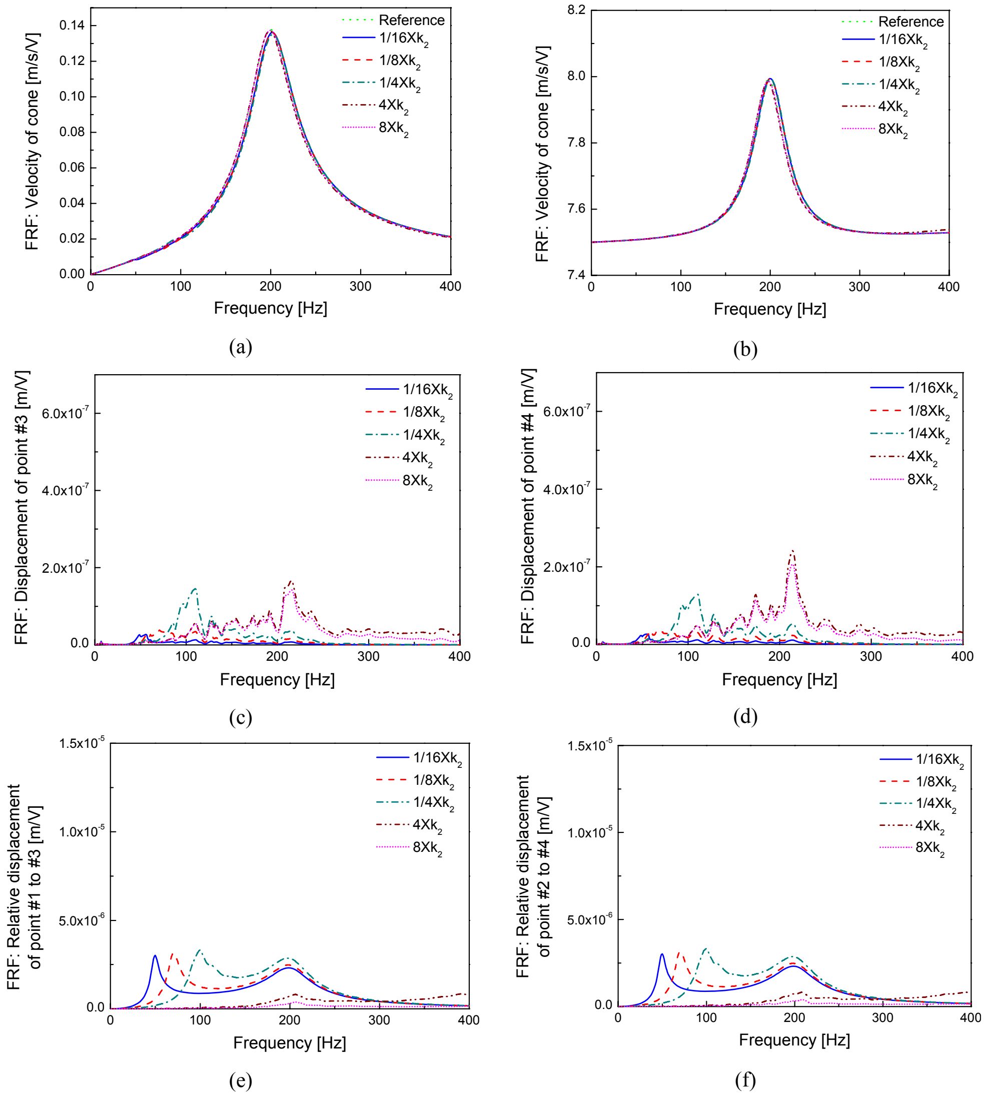

Fig. 5. System responses with respect to the voltage input with various stiffness of isolators, FRF: (a) Velocity of cone; (b) Electric impedance; (c) Displacement of point #3 on TV frame; (d) Displacement of point #4 on TV frame; (e) Relative displacement of point #1 to #3; (f) Relative displacement of point #2 to #4.

nesses of the second sample make smaller vibrations on TV frame than the 4 and 8 time ones do. However, 1/16 and 1/8 time stiffnesses cause larger relative vibrations of speaker frame to TV frame than 4 and 8 time ones do. In case that the large vibration occurs on the speaker frame, another structural vibration noise can come about due to the collision of the speaker and TV frame. Therefore, designer should select appropriate isolator and an adequate gap size between the speaker and TV frame through this substructure synthesis method.

The material of isolator for speakers is normally rubber and its loss factor is known to be from 0.1 to 1.0 [4]. To investigate the effect of loss factor for isolator, loss factor has been changed from 0.1 to 0.7 with the stiffness of sample #2 and the results are shown in Fig. 6. Ones generally think that vibrations of speaker cone will decrease, if loss factor of isolators increases. However, vibrations of speaker cone become bigger with increase of loss factor, which means that distortion on FRF of speaker cone becomes less, as shown in Fig. 6(a). Also, the vibrations of TV and speaker frame become smaller. Therefore, it can be said that large loss factor can prevent distortion of speaker cone and diminish vibrations of TV frame. Even though the simulation result with stiffness of sample #2 is only presented in Fig. 6, the results with other stiffnesses are same.

From the above results, it is concluded that using some stiffnesses can deteriorate the vibration of a cone and enlarge the vibration on a TV frame simultaneously, in this study it happens with three samples. Therefore, using the isolators with these stiffnesses should be avoided. Furthermore, it was found that soft isolators can reduce vibrations on TV frame more than hard isolators do. Moreover, large loss factor less-

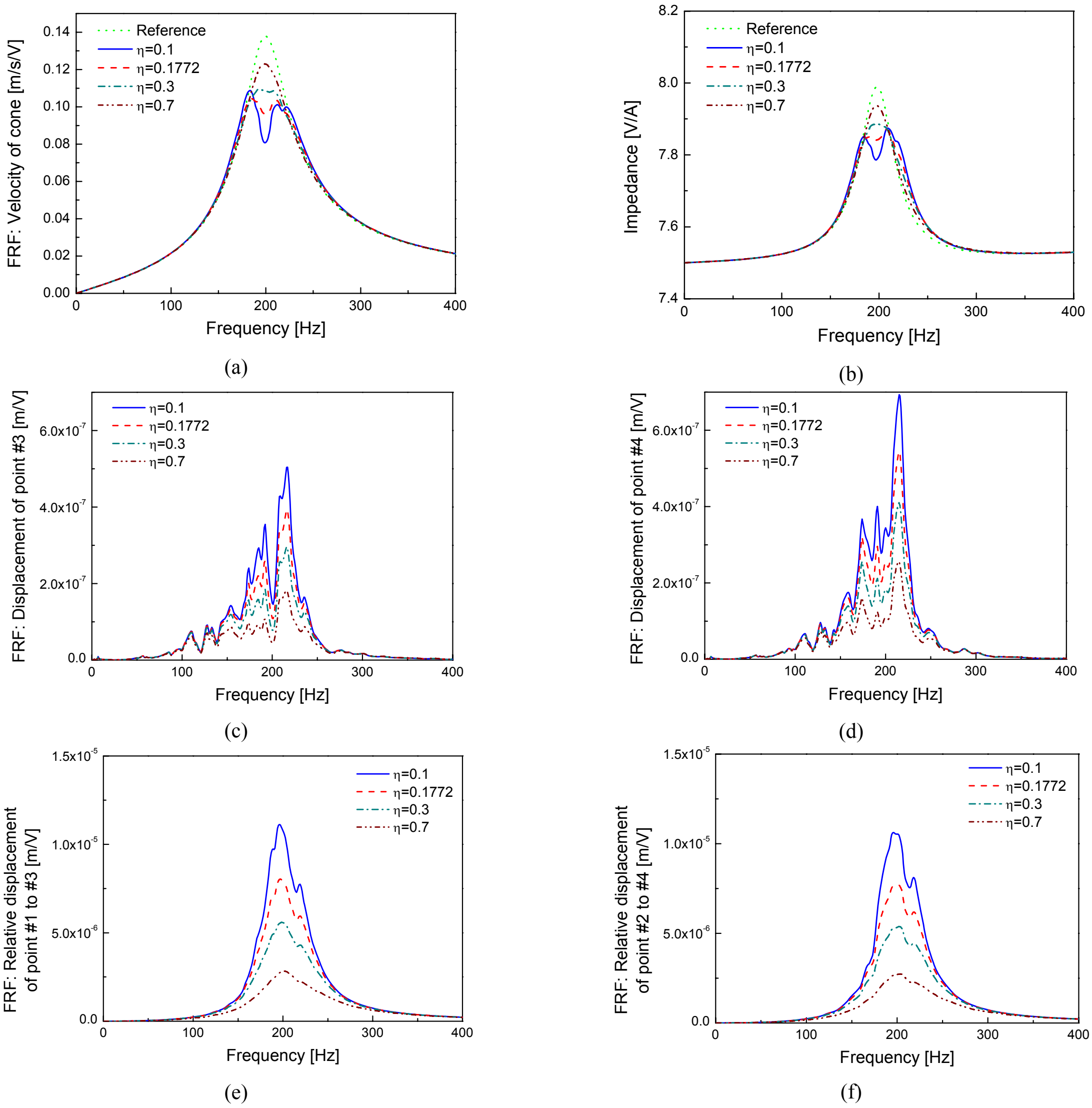

Fig. 6. System responses with respect to the voltage input with various loss factors of isolators, FRF: (a) Velocity of cone; (b) Electric impedance; (c) Displacement of point #3 on TV frame; (d) Displacement of point #4 on TV frame; (e) Relative displacement of point #1 to #3; (f) Relative displacement of point #2 to #4 (with stiffness of sample #2, which is equal to 55.72 kN/m).

ens the distortion on vibrations of speaker cone and reduces vibrations of TV frame. By following the procedure proposed in this study, designers can determine the stiffness and loss factor of a speaker isolator to reduce the vibration on the frame of audio-visual electronic devices without deteriorating the vibration of speaker cone.

4. Conclusion

In this paper, it was pointed out that the speaker operations in audio-visual electronic devices can cause the vibration of the device frame, so that it makes the structural vibration noise. How to reduce the vibration on the device frame without reducing the vibration of speaker cone was stated.

To reduce those structural vibrations, it was chosen to change the stiffness and loss factor of isolators between the speaker and TV frame. The goal of this study was to decrease the vibration of TV frame so as to eliminate the structural vibration noise without reducing the vibration of speaker cone. For this purpose, a model for the whole system was needed, including a TV frame and a speaker. The exciting frequency range by speakers is audible frequency range, which is from 20 to 20 kHz, where a TV frame shows many elastic modes. Therefore, the substructure synthesis method was introduced. An electro-mechanical model for a speaker and a TV frame has been derived based on the substructure synthesis method. A speaker model was derived mathematically and the compliance for a TV frame was obtained experimentally. Then, they were coupled using the FRF coupling technique.

The effects of the stiffness and loss factor for isolators on the vibration of the TV frame and the speaker cone have been investigated through simulations using the derived model. By changing the stiffness and loss factor of isolators, the motion of cone and the vibration of TV frame observed. From the simulation results, it is concluded that using some stiffness can deteriorate the vibration of the cone and enlarge the vibration on the TV frame simultaneously; in case of this study, it happens by using three sample isolators. Furthermore, it is observed that the vibration on the TV frame can be reduced with smaller stiffness than samples. However, soft isolators cannot effectively reduce the relative vibrations of speaker to TV frame which can make another structural vibration noise. Therefore, designers should adjust the gap size between speaker and TV frame to prevent the collision between speaker and TV frame. Moreover, large loss factor of isolators can reduce the vibrations of TV frame and lessen the distortion on motion of speaker cone. By following the procedure proposed in this study, we can determine the stiffness and loss factor of speaker isolator to reduce the vibration on the frame of audio-visual electronic devices without deteriorating the vibration of speaker cone.

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Nomenclature

B : Magnetic flux density
c_c : Viscous damping coefficient of the spider and surround
d_c : Hysteretic damping coefficient of the spider and surround
f_e : Counter electromotive force
f_1, f_2, f_3, f_4 : Forces exerted on the point #1, #2, #3 and #4 in Fig. 1(d)
H : Frequency response function
I_f : Moment of inertia of the speaker frame
i : Current in the voice coil
k_c : Stiffness of the spider and surround
L : Inductance of the voice coil
l_s : Distance between point #1 and #2 on the speaker frame
l_w : Length of the voice coil
m_c : Mass of the cone and bobbin
m_f : Mass of the speaker frame
R : Resistance of the voice coil
v : Voltage to the voice coil
x_c : Translational displacement of the cone
x_f : Translational displacement of the speaker frame
θ : Rotational displacement of the speaker frame

Left subscript

S : Speaker subsystem
T : TV subsystem
I : Isolator subsystem

Right subscript

u : Unconnected
i : Connected to the isolator
v : Voltage
f : Force

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