THEORETICAL AND EXPERIMENTAL STUDY ON VIBRATION TRANSMISSION OF AN AUDIO-BASE FORMED INTO SOLID CONICAL HORN

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Vibration caused on audio equipment seems to induce some problems on reproduced sound quality as electrical noise as result of interaction with geomagnetism. But its mechanism how to convert the vibration on audio equipment into electrical noise is unknown. On the other hand, many kinds of methods to reduce vibration on audio equipment are introduced in actual new product according to the grade, but after purchase of audio equipment, how a consumer can deal with those noises? To deal reproduced sound of audio-equipment, audio-base is widely used among audio mania. Though, there are many kinds of audio-bases on the market and their effects seem not always better one for reproduced sound quality, because of uncertain mechanism of audio-base. As an experimental study, we confirmed that the decrease in vibration on audio equipment is effective the decrease in noise on output signal. Furthermore, in previous study, to confirm the work of audio-base, we derived theoretical analysis of vibration transmission characteristic for exponentially shaped solid horn. In this study, as an audio-base formed into conical horn is most popular, first, we try to derive theoretical analysis of driving impedance for conical horn to describe its working mechanism. The vibration transmission characteristic is evaluated for both transmission direction from “Throat” to “Mouth” and opposite direction under excitation at “Throat” or “Mouth”. Then, the difference in transmission characteristics owing to the transmitting direction is evaluated as difference in driving impedance based on the impedance matching theory. Consequently, we could clarify that the audio-base has changing frequency point to pass through or insulate the vibration related with material and shape. This tendency is also confirmed experimentally by measuring the difference in vibration velocity between input and output surfaces of audio-base. This selective transferring characteristic will be useful to eliminate or insulate inevitable vibration.

Keywords: audio-base, vibration transmission, four-terminal network, four-terminal constants

1. Introduction

There are many kinds of audio-bases on the market and they are used to modify the reproduced sound of stereophonic equipment. They are very convenient to use just putting stereophonic equipment on them and they are effective for CD player, Amplifier and Speaker system etc. Considering their usage, their working should be limited in mechanical action just changing the vibration state of
loaded equipment. While, stereophonic equipment has vibration origin like as built-in power transformer or CD driver and furthermore airborne sound own reproduced music sound will excite itself. The audio-base is excited its top face by loaded equipment, then it transmits the vibration to another end. This vibration transmission characteristic seems of great importance on its reproduced sound quality related with induced noise by interaction between vibration and external magnetism like geomagnetism. Previously, we clarified how the audio-base has an effect to the stereophonic equipment and its sound quality from experimental viewpoint [1-2].

Though, the audio-bases are used widely, their mechanism how to change the vibration state of equipment was not clarified. In previous studies [3-4], we derived the vibration transmission characteristics of audio-base of exponential horn type based on wave equation. Furthermore, we derived four-terminal constants of four-terminal network in electric circuit technique to describe the vibration transmission characteristic. The four-terminal constants are also used in simulation technique of architectural acoustics to evaluate sound transmission loss and absorption coefficient.

In this study, to confirm the above fact that the audio-base shaped in conical horn shows a vibration elimination characteristic to loaded equipment from theoretical viewpoint, the solutions of a wave equation have been derived under connection of load impedance to the output of horn. The difference in vibration transmission characteristic owing to transmitting direction was illustrated as driving impedance at “throat” or “mouth” of the horn. Because the amount of transmitted vibration energy into horn can be evaluated by ratio of driving impedance to inner impedance of exciting source. As the vibration transmission characteristic is influenced by shape factor like as vertical angle, height of horn, density and/or wave propagation velocity of material, we had carried out numerical calculation to illustrate the turning point of insulation or elimination effect for vibration transmission on loaded equipment. Finally, an experimental measurement was carried out and we could confirm an approximate correspondence of turning point between theoretical and experimental ones.

2. Analysis of vibration transmission characteristics of conical horn

Theoretical analysis of vibration transmission characteristic for a solid horn used as a vibration transmitter was carried out in ultrasonic frequency region. In previous study, we proposed a new type of audio-base shaped in exponential horn and derived vibration transmission characteristics under the cut-off frequency by solving wave equation [2-3]. While, a conical horn type of audio-bases is most popular among many kinds of audio bases on the market. Here, we employ a conical horn shaped audio-base as shown in Fig. 1(a). The horn is put in a cup and the “throat” is connected to its bottom and followed a column to “mouth” made by same material with horn itself to keep enough space of driving and transmitted parts. The column and the cup are isolated by O-ring made by rubber. Fig. 1(b) shows the cross-section of the horn. The horn is shaped between \( x=a \) and \( x=h \), and we defined as sectional area at \( x=a \) is "throat" and area at \( x=h \) is "mouth". Then, the horn is excited by external vibration origin through bottom of cup or column connected with horn. By considering this structure,
in any case the horn is connected to impedance $Z_0$ of the cup at "throat" side or impedance $Z_L$ of column at "mouth" side (see Fig. 2 (a) and (b)) made by same material with the horn.

### 2.1 Wave equation in the horn

For an audio-base, inner of horn is filled with solid material of density $\rho$. Then, the pressure wave $p(x)$ propagating in the horn satisfies following wave equation as shown in literacy [5,6],

$$\frac{\partial^2 p(x)}{\partial x^2} + \frac{1}{S(x)} \frac{dS(x)}{dx} \frac{dp(x)}{dx} = \frac{1}{c^2} \frac{\partial^2 p(x)}{\partial t^2},$$  \hspace{1cm} (1)

where $c$ is the propagating velocity and $S(x)$ is cross-section area of the horn at $x$. When the horn is used as audio-base, the vibration transmission characteristics is most important to describe its mechanism to insulate or pass through vibration of loaded equipment, because their effect on the stereophonic equipment should be limited in mechanical mean. On the other hand, as the usage of horn is selective to connect the load with “mouth” or “throat”, the difference in vibration transmission characteristic should be compared the “throat” excitation case (i.e. normal direction) with “mouth” excitation case (i.e. inverse direction).

### 2.2 Driving impedance at "throat" toward “mouth”

For normal direction, $S(x)$ is given by

$$S(x) = \pi \left( x \tan \frac{\theta}{2} \right)^2.$$  \hspace{1cm} (2)

Here, $\theta$ is vertical angle. Then Eq. (1) becomes as

$$\frac{d^2 p(x)}{dx^2} + \frac{2}{x} \frac{dp(x)}{dx} = \frac{1}{c^2} \frac{d^2 p(x)}{dt^2}.$$  \hspace{1cm} (3)

The general solution of Eq. (3) is given as:

$$p(x) = \frac{1}{x} \left( A_n e^{-j k x} + B_n e^{j k x} \right) e^{j \omega t}. \hspace{1cm} (4)$$

Then we have vibration velocity as

$$\dot{u}(x) = -\frac{1}{jkpc} \frac{\partial p(x)}{\partial x} = \frac{1}{jkpcx^2} \left[ A_n (1 + j k x) e^{-j k x} + B_n (1 - j k x) e^{j k x} \right] e^{j \omega t}, \hspace{1cm} (5)$$

where $k = \omega / c$ is wave number and $A_n$ and $B_n$ are constants depend on boundary condition at both ends of horn. To evaluate the difference in vibration transmission characteristic due to transmission direction, the driving impedance at exciting point is useful by considering impedance matching theory.

Here, let us suppose simply the connected impedances $Z_0$ and $Z_L$ as $\rho c$ of material to solve Eqs. (4) and (5). Then, boundary conditions become as $\dot{u}(a) = \dot{u}_0 e^{j \omega t}$ at $x = a$ and $p(h) = \rho c \ddot{u}(h)$ at $x = h$, and we have

$$p(x) = \frac{jkpc^2 \ddot{u}_0}{x} \left[ 1 - \frac{1}{jkh} (1 - j k h) \right] e^{j k (h-a)} - \left[ 1 - \frac{1}{jkh} (1 + j k h) \right] e^{-j k (h-a)} \hspace{1cm} (6)$$

and

$$\dot{u}(x) = \frac{a^2}{x^2} \ddot{u}_0 \left[ 1 - \frac{1}{jkh} (1 - j k h) \right] (1 + j k a) e^{j k (h-a)} - \left[ 1 - \frac{1}{jkh} (1 + j k h) \right] (1 - j k a) e^{-j k (h-a)} e^{j \omega t}. \hspace{1cm} (7)$$

Then, the driving impedance $Z_a$ at “throat” is given as
The consumed energy under the horn is given by

\[ \rho c \frac{u}{\Omega} \]

\[ = \frac{\frac{jkpc}{S_a}}{\frac{\left\{ 1 - \frac{1}{jk\left(1 - jk\alpha\right)} \right\} e^{jk(h - a)} - \left\{ 1 - \frac{1}{jk\left(1 + jk\alpha\right)} \right\} e^{-jk(h - a)}}{\left\{ 1 - \frac{1}{jk\left(1 + jk\alpha\right)} \right\} (1 + jk\alpha)e^{jk(h - a)} - \left\{ 1 - \frac{1}{jk\left(1 - jk\alpha\right)} \right\} (1 - jk\alpha)e^{-jk(h - a)}}. \]  

By rationalization of the denominator, we have

\[ Z_a = \frac{\rho c k^3 h^2 a + j((kh)^2 - k^2h^2 + (1 + 2k^2h)\sin^2\alpha - k(2h - a)\sin\alpha\cos\alpha)}{S_a} \]

\[ \times \left\{ kh\sin\alpha + ka\cos\alpha \right\}^2 + \left\{ (1 + k^2h)\sin\alpha - k(h - a)\cos\alpha \right\}^2 \]

with \( \alpha = k(h - a) \).

### 2.3 Driving impedance at “mouth” toward “throat”

For the “Inverse” direction, by referring Fig.1 (b), the cross-section area of the horn at \( x \) is given by

\[ S(x) = \pi \left\{ (h - x)\tan\frac{\theta}{2} \right\}. \]

Then Eq. (1) becomes as

\[ \frac{d^2p(x)}{dx^2} - \frac{2}{h - x} \frac{dp(x)}{dx} = \frac{1}{c^2} \frac{d^2p(x)}{dt^2}. \]

When the horn is used as audio-base, “mouth” is at \( x = 0 \) and “throat” is at \( x = h - a \). By solving Eq. (11) under the same boundary condition in previous section, we have the driving impedance \( Z_h \) as follows

\[ Z_h = \frac{\frac{jkpc}{S_h}}{\frac{\left\{ 1 + \frac{1}{jk\alpha}(1 + jk\alpha) \right\} e^{jk(h - a)} - \left\{ 1 - \frac{1}{jk\alpha}(1 - jk\alpha) \right\} e^{-jk(h - a)}}{\left\{ 1 + \frac{1}{jk\alpha}(1 - jk\alpha) \right\} (1 - jk\alpha)e^{jk(h - a)} - \left\{ 1 - \frac{1}{jk\alpha}(1 + jk\alpha) \right\} (1 + jk\alpha)e^{-jk(h - a)}}. \]

By rationalization of the denominator, we have

\[ Z_h = \frac{\rho c kh k^3 a^2 h + j(-k^2a^2 + k^2h^2 - (1 + 2k^2ha)\sin^2\alpha + k(h - 2a)\sin\alpha\cos\alpha)}{S_h} \]

\[ \times \left\{ ka\sin\alpha - kh\cos\alpha \right\}^2 + \left\{ (1 + k^2h)\sin\alpha - k(h - a)\cos\alpha \right\}^2 \]

with \( \alpha = k(h - a) \).

### 2.4 Evaluation of transmitted vibration energy into the horn

The transmitted and consumed vibration energy in audio-base can be evaluated by analogy between mechanical vibration and electric circuit. Now consider the pressure \( p(x) \) and vibration velocity \( u(x) \) at \( x = 0 \) as voltage and current respectively in an electric circuit. Let us consider the loaded equipment on the audio-base as vibration source having internal impedance \( Z_0 = r + jX \) and driving impedance of the audio-base as \( Z_1 = R + jX \) as shown Fig. 3. The vibration energy \( P \) transmitted into the horn is given by

\[ P = \text{Re}[pu] = \rho c u^2, \]

under \( Z_0 = \rho c \). In Fig. 3, the current \( |I| \) is given as

\[ |I| = \frac{E}{\sqrt{(r + R)^2 + (x + X)^2}}. \]

The consumed energy \( P \) is given as
\[ P = E^2 \frac{R}{(r + R)^2 + (x + X)^2}. \] (16)

Fig. 4 illustrates the consumed energy \( P \) at \( R \) for \( R/r \). From this figure, the nearer \( Z_1 \) to \( Z_0 \), the more vibration energy is transmitted to \( Z_1 \). This fact is well known as impedance matching.

Figure 3. An electric circuit model to describe the connection of impedance and energy transmission.

![Electric Circuit Model](image_url)

Figure 4. Frequency characteristic of vibration energy consumed at real part of input impedance \( Z_1 \).

![Frequency Characteristic](image_url)

Figure 5. Comparisons of driving impedance for conical horn related to transmitting direction for three kinds of vertical angles.

![Comparisons of Driving Impedance](image_url)
3. Numerical calculation of driving impedance of horn

Based on the experimental result of working of audio-base to a loaded equipment [1], we carried out numerical calculation to evaluate transmitted vibration energy from equipment to audio-base. As mentioned in previous section, the ability to transmit the vibration energy into the horn can be evaluated by its driving impedance at input of horn given in normal direction versus in inverse direction. The energy transmission characteristics are evaluated for some parameters like as shape and material of horn by using Eqs. (8) and (12). First, we carried out a numerical calculation for material of brass. The used parameters are shown in Table 1.

Fig. 5 illustrates the comparisons of driving impedances for normal direction and inverse direction under several vertical angles of $\theta = 30, 90$ and $120$ [deg] with fixed diameters $d_a$ and $d_h$ (i.e. cross sections $S_a$ and $S_h$) as shown in Table 1. In these figures, driving impedances for normal direction keep approximately fixed value related with cross section $S_a$ and $\rho c$ in lower frequency region. On the other hand, the driving impedances for inverse direction decrease with the increase of frequency. Based on the previous discussion on impedance matching, the closer driving impedance to $\rho c$, the more vibration energy is transmitted to the horn. In these figures, the driving impedance for inverse direction approach $\rho c$ than that for normal direction after specific frequency point approximately 2.2 kHz for $\theta = 30$[deg], 8.3 kHz for $\theta = 90$[deg] and 14.4 kHz for $\theta = 120$[deg]. That is, the more vertical angle increase, the more the specific frequency alternate point increase under fixed cross sections $S_a$ and $S_h$. Then, we could reach to conclusion that audio-base prevents well vibration in lower region of the specific frequency but eliminates it well in higher region of it for inverse direction comparing with normal direction.

Next, to illustrate the influence of material of horn, we carried out numerical calculation for four kinds of materials as Brass, Nylon 66, Magnesium and Aluminium with use of parameters shown in Table 2. Results of specific frequency points are illustrated in Fig. 6. Comparing these results, for the same shape of horn, the specific frequency point is approximately proportional to wave propagating velocity.

Table 1. Parameters used in numerical calculation to evaluate the specific frequency point alternating the driving impedance for normal direction and inverse direction owing to vertical angle.

<table>
<thead>
<tr>
<th>Properties And Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Brass) $\rho$ [kg/m$^3$]</td>
<td>8600</td>
</tr>
<tr>
<td>Velocity (Brass) $c$ [m/s]</td>
<td>4430</td>
</tr>
<tr>
<td>Diameter of Throat $d_a$ [m]</td>
<td>0.001</td>
</tr>
<tr>
<td>Diameter of Mouth $d_h$ [m]</td>
<td>0.020</td>
</tr>
<tr>
<td>Vertical Angle $\theta$ [deg]</td>
<td>30, 90, 120</td>
</tr>
<tr>
<td>Height $h-a$ [m]</td>
<td>0.0354, 0.095, 0.0055</td>
</tr>
<tr>
<td>Alternating Frequency $f$ [Hz]</td>
<td>2200, 8300, 14400</td>
</tr>
</tbody>
</table>
Table 2. Parameters used in numerical calculation to evaluate the specific frequency point alternating the driving impedance for normal direction and inverse direction for several materials.

<table>
<thead>
<tr>
<th>Shaping Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Angle $\theta$ [deg]</td>
<td>90</td>
</tr>
<tr>
<td>Height $h$ [m]</td>
<td>0.095</td>
</tr>
<tr>
<td>Diameter of Throat $d_a$ [m]</td>
<td>0.001</td>
</tr>
<tr>
<td>Diameter of Mouth $d_b$ [m]</td>
<td>0.020</td>
</tr>
<tr>
<td>Properties of Material</td>
<td>Brass</td>
</tr>
<tr>
<td>Density $\rho$ [kg/m$^3$]</td>
<td>8600</td>
</tr>
<tr>
<td>Velocity $c$ [m/s]</td>
<td>3480</td>
</tr>
<tr>
<td>Alternating Frequency $f$ [Hz]</td>
<td>8300</td>
</tr>
</tbody>
</table>

4. Experimental study on vibration transmission characteristic

Next, to confirm experimentally the theoretical results, we carried out an experiment to observe a vibration transmission characteristic of audio-base. Here, we employed an audio-base shaped in conical horn under $\theta = 90$[deg] made by brass with surrounding cup as shown in Fig. 1(a) whose parameters are given in Table 1. The diagram of measuring system for vibration transmission characteristics is shown in Fig. 7. The surface of “throat” or “mouth” was excited by a piezo exciting unit through glass plate and cup or column with sinusoidal signal of several frequencies and vibration velocity amplitude on exciting point (input) and transmitted side (output) were measured by laser Doppler vibrometers and a FFT analyser.

Fig. 8 shows the result of difference of vibration velocity amplitude level between input and output surfaces for both direction. Here, the difference between “Normal” and “Inverse” directions means the ability to insulate or eliminate the vibration toward output. In this figure, in higher frequency region than about 6.3 kHz, the vibration level difference for “Inverse” direction become smaller that for “Normal” direction. This frequency point 6.3 kHz approximately corresponds to the alternate points given in Figs. 5. And the same tendency in Fig. 8 is also shown in Fig. 5. This means that the audio-base works as insulator to prevent vibration from floor for “Normal” direction but discharger to eliminate the vibration to floor for “Inverse” direction in higher frequency region of specific frequency point alternating the transmission characteristic between both directions. So, an audio-base is expected to reduce vibration on the loaded equipment in higher frequency region.
5. Conclusions

In this study, we have tried to clarify the working mechanism of audio-bases especially shaped in conical horn by theoretical analysis on vibration transmission in the horn. The vibration transmission characteristics of the audio-base was evaluated by driving impedance of horn under excitation at “throat” or “mouth”. Based on the numerical result, it was clarified that a horn shaped audio-base has a frequency point alternate its work from insulate to eliminate vibration of loaded equipment. In higher frequency region than this specific frequency point, the horn passes through vibration energy well from “mouth” to “throat” direction (i.e. inverse direction) than that for opposite direction and in lower frequency region the horn prevents vibration transmission. Especially, this specific frequency point is controllable by vertical angle and vibration traveling velocity of material of horn. Furthermore, these theoretically results of vibration transmission characteristics show same tendency of experimentally observed results for audio-base with conical horn. Based on above theoretical and experimental results, we could draw a conclusion that the audio-base is effective in discharging vibration of audio equipment put on it and in insulating it from floor in a specific frequency region.

REFERENCES


