Influence of music-induced floor vibration on impression of music in concert halls

Takahisa Miyata\(^{(a)}\), Kazuma Hoshi\(^{(b)}\), Toshiki Hanyu\(^{(c)}\)

\(^{(a)}\) Nihon University, Japan, h.lab.miyata@gmail.com
\(^{(b)}\) Nihon University, Japan, hoshi@arch.jcn.nihon-u.ac.jp
\(^{(c)}\) Nihon University, Japan, hanyu@arch.jcn.nihon-u.ac.jp

Abstract

Sound can be perceived in two ways: using the auditory sense, and as vibrations, using the tactile sense. Several musicians and music-lovers recognize that the floor and audience seats vibrate during chamber music performed in concert halls. There are several studies on the psychoacoustic role of vibration in the field of room acoustics. Most recent studies have investigated only the vibration generated on the stage, but there are a few studies on the vibration of the audience floor. Depending on the structure and materials used in construction, the vibrations caused by the musical performances may become sufficiently strong to be perceived by the audience, which, it can be supposed, may affect the auditory impression of music. In order to confirm this hypothesis, an apparatus was prepared to simulate the vibration of the audience floor. This study discusses mainly two experiments using the apparatus. First, subjects listened to music with or without vibration synchronized with the music using the apparatus. After listening to the music, the Evaluation Grid Method was used to extract words of impression. Second, we investigated whether the impressions of the music were influenced by the magnitude of vibration. Additionally, in order to confirm whether vibration really occurs in real concert halls, vibrations were measured in the concert halls.

Keywords: concert hall, floor vibration, vibroacoustics, auditory impression, cognitive structure
Influence of music-induced floor vibration on impression of music in concert halls

1 Introduction

There is a growing interest in vibroacoustic effects in performance spaces like concert halls. Therefore, there are several studies about vibroacoustic effects on stage. Furthermore, some music lovers and researchers believe that perceptible vibrations sometimes occur in the auditorium, and that they have a positive effect on the listener. Therefore, a few studies about vibroacoustic effects in the auditorium have been published [1, 3]. In these studies, it is suggested that the sound from a musical performance is transmitted to the audience as vibration. In addition, there are some studies that suggest that vibration has a positive effect on the audience’s reception of the performance [2, 4]. From these studies, it can be seen that vibration has a significant role in concert halls and should be of interest to researchers.

This paper mainly discusses the relationship between the auditory and vibratory components of a music performance and audience impression. The first study brings out the hidden auditory cognitive structure of vibration. It shows that vibration causes variations in many auditory impressions. The second study discusses the relationship between the intensity of vibration and auditory impressions. Additionally, vibration induced by sound in an actual concert hall is examined.

2 Experimental apparatus

The experimental apparatus is shown in Figure 1. It simulates the floor vibrations of a concert hall. An auditory signal is produced by a headphone, while vibrations are produced by a vibration exciter attached to a piece of plywood (1.5 m × 0.9 m × 12 mm). Rubber pads placed beneath the plywood separate the vibrations of the apparatus and the ground. The subject is seated on a chair next to the plywood, with his feet on the plywood, approximately 1.3 m from the exciter. This apparatus is designed to transmit vibration only to the subject’s legs. Subjects were asked to take off their shoes to make the experimental conditions uniform.

![Experimental apparatus diagram](image)
3 Extraction of auditory impression of vibration

3.1 Evaluation Grid Method

Evaluation Grid Method (EGM) is a method used to investigate the question of how people evaluate the stimuli they perceive. This method is based on the Personal Construct Theory developed by George A. Kelly (1955). This theory can roughly be explained as, “When people perceive stimulus, they build a characteristic cognitive structure and evaluate them based on the cognitive structure.” Kelly applied it to the field of environmental psychology and developed the Role Construct Repertory Test (RCRT). The EGM was further developed from RCRT. The EGM uses a unique questioning method called the Laddering Method, which is useful in extracting human cognitive structure effectively.

![Diagram of concept hierarchy]

**Figure 2: Cognitive structure in Personal Construct Theory**

3.2 Experimental Outline

Experimental auditory and vibratory signal:

The musical piece used in the experiment was “The Planets, op. 32: Mars, the Bringer of War (1956, L. Stokowskij).” This piece is too long, and therefore, only a 20-s clip was used as the experimental stimulus. The 20-s selection was chosen for its impressive bass sound. The vibratory signal generated was then passed through a low-pass filter with a cut-off frequency of 150 Hz.

Experimental design:

In this study, two stimuli were prepared. One consisted of listening to music with vibration (type A), while the other involved just listening to music (type B). The subjects, who were 20 college students, compared the two types of stimuli and answered a set of questions based on the EGM. As a result, the auditory effects caused by the vibration were extracted as a cognitive structure. Subjects were not informed about the experimental details. While listening to the stimuli, the subjects were blindfolded so as to not see the experimental apparatus.
3.3 Results and Discussion

As a result, 20 cognitive structure diagrams were obtained. These diagrams are summarized in the conceptual diagram shown in Figure 3. The right-hand side of the diagram (lower concept) shows the objective judgments about the auditory effects of the vibration. The central section (middle concept) shows the impressions formed about the auditory effects of the vibration. The left-hand side (upper concept) shows the value judgments about the auditory effects of the vibration. The numbers in Figure 3 indicate duplicate answers by subjects. These results show that the vibration provides a variety of auditory effects. A number of words related to the auditory impression can be extracted as follows: “presence,” “powerfulness,” “multidirectionality,” “reverberation,” “clarity,” “emotionality,” etc.

![Conceptual diagram of vibration effect to music](image)

4 Relationship between intensity of vibration and degree of auditory impression

4.1 Experimental outline

Experimental auditory and vibratory signal:

The audio used to measure impression and intensity followed the same procedure as previously outlined with two exceptions. The musical piece used as a stimulus was “The Planets, op. 32: Jupiter, the Bringer of Jollity (1981, H. Karajan).” The vibratory stimulus was passed through a low-pass filter with a 110 Hz cut-off frequency.
Experimental comparative stimuli:

For this study, the intensity of vibration was divided into six levels, as shown in Table 1. No vibratory signal was generated at level 0 (background vibration acceleration level of approximately 37 dB). Level 1 was slightly perceptible. Level 5 of vibration intensity would be too high to feel in concert halls. These stimuli are used in Scheffe’s paired comparison method. Thirty pairs of comparative stimuli were prepared. Subjects adjusted volume of the playback sound before starting the experiment.

<table>
<thead>
<tr>
<th>Level</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration Level [dB]</td>
<td>37</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>70</td>
<td>75</td>
</tr>
</tbody>
</table>

Experimental auditory impression words:

Eight words describing auditory impressions were selected from Figure 3. “Preference” was added as an overall evaluation word. Table 2 shows the nine selected auditory impression words and their meanings. The subjects judged the difference in the auditory impressions between a pair of stimuli using a seven-point rating scale shown in Figure 4.

<table>
<thead>
<tr>
<th>Auditory Impression words</th>
<th>Meaning of the words</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loudness</td>
<td>A measure of sound magnitude</td>
</tr>
<tr>
<td>Reverberation</td>
<td>A measure of how long the sound lasts</td>
</tr>
<tr>
<td>Clarity</td>
<td>A measure of the sound being heard clearly</td>
</tr>
<tr>
<td>Multidirectionality</td>
<td>A measure of being surrounded by sound</td>
</tr>
<tr>
<td>Presence</td>
<td>A measure of reality of concert experience</td>
</tr>
<tr>
<td>Powerfulness</td>
<td>A measure of the sound being forceful</td>
</tr>
<tr>
<td>Emotionality</td>
<td>A measure of being impressed</td>
</tr>
<tr>
<td>Immersion</td>
<td>A measure of being immersed in sound</td>
</tr>
<tr>
<td>Preference</td>
<td>A measure of overall evaluation</td>
</tr>
</tbody>
</table>

4.2 Results and Discussion

The results of the subjective test are shown in Figures 5, 6, and 7. These results can be divided into three categories as follows: no significant difference in the vibration intensity, a significant difference at a certain level, and upward tendency in response to vibration intensity.
No significant difference in the vibration intensity:

As shown in Figure 5, “loudness” and “clarity” were not significantly different (p > 0.05) with regard to the level of vibration intensity. This result means that floor vibration did not affect either Loudness or Clarity.

![Figure 5: Relationship between vibration intensity and auditory impressions: “loudness” and “clarity”](image)

A significant difference at a certain level:

Reverberation and preference show a slightly significant difference (p > 0.05) with regard to the vibration intensity. If the vibration is stronger than level 4 (70 dB), it may influence the auditory impression of reverberation. In addition, “preference” scores show that vibration tends to be favored at higher levels.

![Figure 6: Relationship between vibration intensity and auditory impressions: “reverberation” and “preference”](image)
Upward tendency in response to vibration intensity:

“Multidirectionality,” “presence,” “powerfulness,” “emotionality,” and “immersion” were significantly different \((p > 0.05)\) at different vibration intensities. Figure 7 shows that these results have an upward trend in response to vibration intensity. These auditory impressions have a positive relationship with vibration intensity.

![Figure 7: Relationship between vibration intensity and auditory impressions: Multidirectionality, Presence, Power, Emotionality, and Immersion](image)

5 Measurement of vibration in a concert hall

5.1 Measurement methodology

A small hexagonal-shaped concert hall with a seating capacity of 437 and the experimental setup used for measurements are shown in Figure 8. Two receiver positions were selected. A dodecahedron loudspeaker and a woofer were used as the sound source. Pink noise was used as the measurement signal. Furthermore, three different sound levels were prepared. Relative output levels were set at three steps of 0 dB, \(-5\) dB, and \(-10\) dB. Sounds and vibrations were measured at the same time. A microphone (ONO SOKKI MI-3111) was set at a height of 10 cm from the audience floor. Two vibration pickups (ONO SOKKI NP-3412) were used. One was attached to the audience floor and another one was attached under a seat. The audience floor was made of concrete, and therefore, unlikely to vibrate during a musical performance. The audience seats were made of wood and upholstered.
5.2 Results and discussion

Figures 9 and 10 show vibration acceleration levels measured at the audience floor and under the seats at R1 and R2. These three vibration acceleration levels, depending on relative output levels, are plotted in figures 9 and 10. In addition, background vibration and self-noise level of the measurement equipment are also plotted. If the vibration was caused by the loudspeaker and woofer, it would be larger than the background vibration.

As seen in Figures 9 and 10, vibration acceleration levels at the audience floor did not exceed the levels of background vibration. Therefore, vibration at the audience floor was not caused by the loudspeaker and woofer. This is because the floor is made of a hard material. On the other hand, seat vibration was caused by the loudspeaker and woofer (at a frequency range of 78–1000 Hz) because its vibration levels exceeded the levels of background vibration. Merchel and Altinsoy (2013) calculated the difference between vibration acceleration level and sound pressure level, $L_{\text{acc}} - L_{\text{SPL}}$. They confirmed the linear relationship between sound intensity and vibration intensity. Figure 11 shows the difference between the vibration acceleration levels and sound pressure levels, $L_{\text{acc}} - L_{\text{SPL}}$, under the seats in our measurement. If the difference does not change independent of the output level of the loudspeaker, there is a linear relationship between the vibration acceleration level and sound pressure level. This means that airborne sound excites the seats.

Our results were similar to the results of Merchel and Altinsoy. Therefore, we conclude that vibration may be induced in the audience seats by the airborne sound. It can be thought that perceptible vibration would occur on the audience floor if the floor were made of wood.
Figure 9: Vibration acceleration levels under the seat and at the floor (R1).

Figure 10: Vibration acceleration levels under the seat and at the floor (R2).

Figure 11: Difference between vibration acceleration levels and sound pressure levels under the seats at R1 and R2.
6 Summary

This paper discussed three types of experiments, and the results can be summarized as follows:

- Vibration synchronized with music can influence the following auditory impressions: “loudness,” “clarity,” “reverberation,” “multidirectionality,” “presence,” “powerfulness,” “emotionally,” and “immersion.”
- The vibration can emphasize the auditory impressions of “multidirectionality,” “presence,” “powerfulness,” “emotionality,” and “immersion.”
- The linear relationship between the vibration acceleration level and sound pressure level was observed in actual concert halls. Therefore, there is a possibility that the audience floor and audience seats vibrate due to musical performances.

References