Analysis of reverberation times and energy decay curves of 1/12 octave bands in performance spaces considering musical scale

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Abstract

Generally in the room acoustic design field, the reverberation times of 1 octave bands or 1/3 octave bands are analyzed for evaluating acoustic conditions in performance spaces such as concert halls. The center frequency in the octave bands is defined by engineering frequency intervals such as 250 Hz, 500 Hz, and 1000 Hz in the conventional analysis method. However, this definition of center frequency is not always adequate for evaluating performance spaces because music is composed of musical notes based on a musical scale, which is different from engineering frequency scales. Therefore, we studied the analysis of reverberation times and energy decay curves in 1/12 octave bands based on an equal tempered scale. Reverberation times in several concert halls were analyzed by this method. Distributions of reverberation times of 1/12 octave bands between concert halls were obtained. Next, instrumental sounds of varying pitches were convolved with impulse responses, and the reverberation times of the different pitches were analyzed from the convolved signals. As a result, variation of the reverberation times of the 1/12 octave bands and that of the different pitches corresponded well. When people listen to music in a performance space, they feel some impressions of the music, of which chords are an important aspect. Thus, chord signals were convolved with impulse responses, and the convolved signals of the reverberation times were analyzed. Finally, distributions of the differences of energy decay curves of chord signals were obtained.

Keywords: 1/12 octave band, equal temperament, reverberation time, musical chord, performance space
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1 Introduction
Reverberation times are an important characteristic of sound fields, concert halls, music theaters, and studios. Currently, reverberation times are calculated using 1 octave and 1/3 octave bands. However, these frequency bands are defined by engineering frequency intervals such as 250 Hz, 500 Hz, and 1000 Hz, regardless of the performance space. Therefore, calculated reverberation times need to correspond to the performance space. In this study, we calculated reverberation times using 1/12 octave bands based on the center frequencies of equal temperament. Moreover, we calculated reverberation times by using sounds from musical instruments at a wide range of equal temperaments. Finally, we found that sound fields have different reverberation decay curves when the sound of chords consisting of pink noise within some 1/12 octave bands were radiated in the performance space.

2 Reverberation time of 1/12 octave band

2.1 Measurement method
Figure 1 shows plan views of 3 different sound fields investigated in this study, and Table 1 shows specifications of the 3 sound fields. There were 6, 4, and 6 receiving points in halls A, B, and C, respectively. Impulse responses were measured at each receiving point. A TSP signal was radiated from a sound source for measuring impulse responses. The sampling frequency was 48 kHz and the quantization was 24 bits.

Table 1: Specifications of measured halls

<table>
<thead>
<tr>
<th>Hall</th>
<th>Volume[m³]</th>
<th>RT(440Hz)</th>
<th>Seating capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall A</td>
<td>6060</td>
<td>1.6</td>
<td>511</td>
</tr>
<tr>
<td>Hall B</td>
<td>4370</td>
<td>0.92</td>
<td>437</td>
</tr>
<tr>
<td>Hall C</td>
<td>1822</td>
<td>1.4</td>
<td>220</td>
</tr>
</tbody>
</table>

2.2 Analysis Method
Table 2 shows the center frequencies of the 1/12 octave bands in the 12-tone equal temperament tuning system (12-TET) based on A at 440 Hz (A440). Impulse responses were filtered for each 1/12 octave band using the center frequencies listed in Table 2. The reverberation decay curves for each 1/12 octave band were subsequently calculated by a backward integration of the squared...
impulse response. The reverberation times were then calculated from the decay curves. Moreover, the decay curves and reverberation times were calculated also for each 1-octave band using center frequencies of A in the equal temperament.

Table 2: Center frequencies of equal temperament of music scale

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>C#</th>
<th>D</th>
<th>D#</th>
<th>E</th>
<th>F</th>
<th>F#</th>
<th>G</th>
<th>G#</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>262</td>
<td>277</td>
<td>294</td>
<td>311</td>
<td>330</td>
<td>349</td>
<td>369</td>
<td>392</td>
<td>415</td>
<td>440</td>
</tr>
<tr>
<td>A#</td>
<td>...</td>
<td>H</td>
<td>...</td>
<td>F</td>
<td>...</td>
<td>G</td>
<td>G#</td>
<td>...</td>
<td>D</td>
<td>...</td>
</tr>
<tr>
<td>466</td>
<td>494</td>
<td>...</td>
<td>699</td>
<td>...</td>
<td>784</td>
<td>830</td>
<td>...</td>
<td>9397</td>
<td>9956</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Results and consideration

Only results from the receiving point (R) at the center of each sound field were shown in Figure 2 because results from other receiving points have similar tendencies. Figure 2 shows frequency characteristics of reverberation time for 1 octave and 1/12 octave bands. Reverberation times in 1/12 octave bands significantly vary from those for 1 octave bands. The variation of reverberation times for 1/12 octave bands is different between the three sound fields. The variation was especially large in hall C. In addition, the Schroeder frequency, $F_s = 2000 \times \sqrt{T/V}$, was calculated for each of the three sound fields, where T is the reverberation time for the 440 Hz octave band, and V is the room volume [m$^3$]. The Schroeder frequencies were 34 Hz, 29 Hz, and 62 Hz, for halls A, B, and C, respectively. These frequencies are very low relative to the frequency range for analyzing reverberation times in Figure 2. This means that the variation of reverberation times occurred in other modal sound fields. Figure 3 shows reverberation decay curves whose range is 293.66–554.37 Hz (D~D#), where it can be seen that reverberation decay curves vary in slope significantly for hall C.

![Figure 2: Frequency characteristics of reverberation time in the three halls](image-url)
2.4 Reverberation time ratio

Variations of reverberation times should be compared between sound fields. However, they cannot be directly compared because reverberation times are different between sound fields. Therefore, we suggest the use of a Reverberation Time Ratio: RTR. This is the reverberation time of each 1/12 octave band that is normalized by an averaged value of reverberation times for 1/12 octave bands which are included in the range of 1 octave band whose center frequency is the same as the targeted 1/12 octave band. Variation of RTR means normalized variation of reverberation times for 1/12 octave bands in each sound field. Equation (1) shows RTR, with

\[ RTR = \frac{RT_n}{RT_{ave,n}} \]  

Figure 4 shows the RTR of the three halls indicated in Figure 1. As shown in Figure 4, the RTR of hall C varies widely, and the variation of RTR became small at higher frequencies. Figure 5 shows the standard deviation of RTR in frequency ranges of C~D#, H~H (low frequency), and C~D# (high frequency) for each sound field. It can be seen that the standard deviation of RTR differs especially in the low frequency range. An F-test for RTR was subsequently performed.

Table 3 shows the F-test values in the frequency range of C~D#, H~H (low frequency), and C~D# (high frequency). As shown in Table 3, statistical differences of RTR can be found between some cases. Halls A and B, which are concert halls, have relatively small variation of RTR. Consequently, it can be said that sound fields with small variation of RTR were well designed acoustically.
3 Analysis using instrument sounds

3.1 Method for analyzing reverberation times using instrument sounds

Reverberation times were calculated using a variety of musical instrument sounds. French horn, oboe, and violin sound samples were chosen from instrument sample CDs [2]. Approximately 2 s of sound at a fixed pitch of each instrument were played for every possible musical scale. The stationary instrument sound was convoluted with impulse responses of three halls shown in Figure 1. Only a decay part of the convolved signals was detected, and then the decay curves for each musical scale were calculated by a backward integration of the detected signals. After that,
reverberation times were calculated from the decay curves. The regression range was -5 dB to -35 dB. Finally, the RTRs were calculated for combinations of sound fields and instruments.

3.2 Results and consideration

Figure 6 shows the RTR of a French horn in the three halls. RTRs using an oboe and a violin are shown in Figures 7 and 8, respectively. In addition, Table 4 shows the F-test results for RTR variations between the three halls. As seen in Figures 6, 7, and 8, variations of RTRs were instrument dependent. The RTR variations for the French horn were relatively large compared to the other two instruments. Particularly for the French horn in Figure 6 and Table 4, the RTR variations of halls B and C were larger than that of hall A. The RTR variations for the oboe in Figure 7 and Table 4 differ only between halls A and B. The RTR variations for the violin in Figure 8 and Table 4 in hall C are significantly larger than those of halls A and B. As a whole, the RTR variations of hall A were relatively small regardless of the instrument type. However, the RTR variations of hall C were larger than those of the other two halls. These phenomena correspond to the results in Figures 4 and 5 discussed in the previous chapter.
4 Analysis using chord sounds

4.1 Method for calculating reverberation decay curves using chord sounds
Chords are one of the important elements for making impressions of musical sound in a performance space. Therefore, reverberation decay curves were obtained using chord sounds. Two chords composed of three tones, CEG and A#F#G#, were used in this study. Impulse responses of the three halls shown in Figure 1 were used. About 2 s of pink noise was filtered for each 1/12 octave band was used for each musical scale, and the pink noise was convoluted with the impulse responses. Decay parts of the convolved signals were detected for calculating reverberation decay curves. The decay curves were calculated by a backward squared integration of the detected signals. The reverberation decay curves were not normalized because comparison of the level difference of the decay curves could be available. The same operation was then repeated three times for each frequency in the chord.

4.2 Results and consideration
Figures 9 and 10 show reverberation decay curves of the chords, CEG and A#F#G#, for each sound field. Reverberation decay curves were different even in the same chord and hall, and were also different even in the same hall if the chords were different. Especially for Hall C, differences of the decay curves were significantly larger relative to that of the other two halls. In hall C, different decay curves in a chord might provide an imbalanced impression of reverberation of the
chord. In such a hall, the impression of the reverberation of the chord might not be satisfactory. This phenomenon discussed in this chapter corresponds to the phenomena investigated in the previous two chapters. Therefore, 1/12 octave band analysis of reverberation time could be useful for evaluating sound fields of musical performance spaces.

Figure 9: Reverberation decay curves of chord sound, CEG

Figure 10: Reverberation decay curves of chord sound, A#F#G#

5 Conclusion

In this study, reverberation times for each 1/12 octave band were analyzed. As a result, varying reverberation times for each 1/12 octave band were found. These variations were not found when using conventional 1 octave band analysis. Additionally, there were correspondences in varying reverberation times from calculated impulse responses between varying reverberation times from calculated instrument sounds. Finally, differences in reverberation decay curves were found within single chords. In such cases, there is the possibility that the impression of the reverberation of the chord might not be satisfactory. Therefore 1/12 octave band analysis of reverberation time could be useful for evaluating sound fields of musical performance spaces.
References


