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Letter to the Editor

Reverberation time measurement for an acoustic room with low value of BT by utilizing wavelet transform

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1. Introduction

There are two serious measurement errors in the backward integrated impulse response method [1] that has been used for a long time to obtain an acoustic decay curve, which is necessary for the measurement of the reverberation time. The one error is due to background noise; the other is caused by the filtering process. According to previous works [1,2], in order to avoid the latter error, the product of the band pass filter bandwidth and reverberation time of the room under test must be at least 16 to obtain acoustic decay curves without the influence of the band pass filter. Therefore, it is difficult to evaluate the reverberation times of particular acoustic rooms, such as talk-studios in broadcasting [3], the compartments of passenger cars [4–6], and sound-control rooms with specific purposes since they have short reverberation times. In order to overcome this problem, Lee [7] suggested a new method recently, called the wavelet transform-based method, for determining acoustic decay curves by using the wavelet filter bank based on continuous wavelet transform. This method replaces the inequality $BT < 16$ with $BT < 4$ without the delay effect of acoustic decay curves. In the present paper, to justify the solid application of the new wavelet filter to the measurement of the reverberation time of a real acoustic room, both filter banks are applied to the measurement of the reverberation times of a real acoustic room. Output of both filtering procedure is demonstrated.

2. Review of filter influence

In order to review the characteristic of both filters, let us consider an acoustic room as a linear system of which the impulse response is $h(t)$:

$$h(t) = \sum_{i=1}^{L} h_i(t) \tag{1a}$$

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and

$$h_i(t) = \begin{cases} e^{t/2\lambda} \cos \omega_i t & \text{for} \quad t > 0, \\ 0 & \text{elsewhere,} \end{cases} \tag{1b}$$

where L is the number of third-octave bands, $T = 6\ln(10)\lambda$ and ω_i is the ith center frequency of the filter bank. If the band pass filter bank is used, the acoustic decay curves at certain frequency ω_i are calculated by convolving the ideal impulse response of a room $h_i(t)$ with the impulse response $h_b(t)$ of the band pass filter with bandwidths B and by backward integrating the squared value of that result. Its mathematical formula is given by [7]

$$d(t) = \int_t^{\infty} \left(\int_{-\infty}^{\infty} e^{3\lambda \ln(10)/T} \cos \omega_i \lambda (h_b(\eta - \lambda))\, d\lambda \right)^2 d\eta, \tag{2}$$

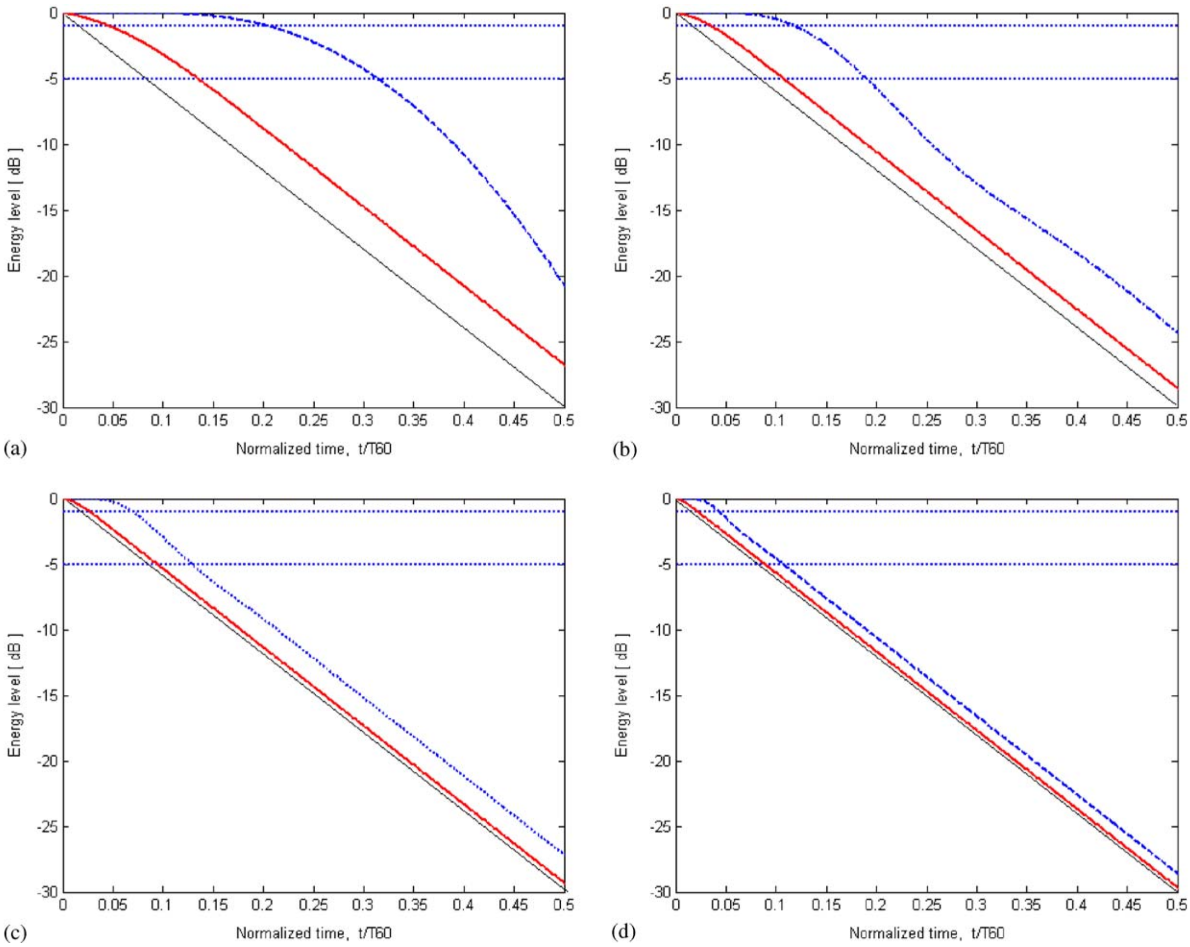


Fig. 1. Comparison of acoustic decay curves calculated by applying the third-octave band pass filter and the third-octave wavelet filter bank to the exponential decay function with the frequency 125 Hz; ——, ideal decay curve; - - - -, third-octave band pass filter; ▬▬, third-octave wavelet filter; (a) $BT_{60} = 4$, (b) $BT_{60} = 8$, (c) $BT_{60} = 16$, (d) $BT_{60} = 32$.

where $h_b(t)$ is the impulse response of the third octave band pass filter with bandwidth B. If the wavelet filter bank is used, the acoustic decay curves at certain frequency ω_i are calculated by backward integrating the squared value of results obtained by taking the wavelet transform of the ideal impulse response of a room $h_i(t)$. Its final formula is given by [7]

$$d(t) = \int_{\infty}^{t} \left[\frac{1}{\sqrt{a}} \int_{0}^{+\infty} \frac{1}{\sqrt{\pi B}} \exp\left(\mathrm{j}(\tau - \eta)\left(\frac{\omega_0 - \omega_i + 1/2\lambda}{a}\right) - \frac{1}{B}\left(\frac{\tau - \eta}{a}\right)^2 \right) \mathrm{d}\tau \right]^2 \mathrm{d}\eta, \quad (3)$$

where $a = \omega_0/\omega_i$ and ω_0 is the center frequency of the "mother wavelet." Fig. 1 shows the comparison between the acoustic decay curves calculated by using the band pass filter bank and those calculated by using the wavelet filter bank. The reverberation time T used for this test is unity and the center frequency is 125 Hz. The bandwidth of filters B is changed to make different values of BT from $BT = 4$ to 32. Ideally, if filters do not affect the ideal impulse response of a room, the impulse response of the combination of the filter and room becomes the ideal impulse response by itself [7]. In the Fig. 1, the narrow solid line means the acoustic decay curve of the ideal impulse response, the dotted line shows the acoustic decay curves calculated by using Eq. (2), and the thick solid line shows the acoustic decay curve obtained by using Eq. (3). According to these results, when $BT < 16$, the distortion of acoustic decay curves obtained by using the band pass filter bank is severe, as shown in Figs. 1(a) and (b). In addition, the initial delay is also long. Therefore, it is concluded that the application of the wavelet filter bank is more useful than the band pass filter bank to obtain an accurate acoustic decay curve for measurement of reverberation time in the range of $4 \leqslant BT \leqslant 16$.

3. Reverberation time for benchmarked signals

In the previous section, the influence of filters was reviewed by using acoustic decay curves. It was found that using the wavelet filter bank is better than the traditional band pass filter to get an accurate acoustic decay curves from the impulse response of a room. For the practical application of a new wavelet filter bank in the field of room acoustics, reverberation time should be measured since it is used for calculating the absorption ratio of absorption materials and for expressing the acoustic characteristics of an acoustic room [8]. The reverberation time of the room is defined as the time required for 60 dB attenuation of the acoustic energy level. The acoustic energy level is expressed as the magnitude of the acoustic decay curves [8], which are obtained by filtering the impulse response of an acoustic room with a filter bank. In order to facilitate the interpretation of the reverberation time resulting from an impulse response of the acoustic room, the reverberation times obtained by using both the band pass filter bank and wavelet filter bank are first demonstrated on benchmarked synthetic signals. The benchmarked synthetic signal used for the impulse response of a room consists of the sum of the ideal decay function in Eq. (1). The ideal decay impulse response $h_i(t)$ at each third-octave center frequency ω_i is made with a sampling frequency of 46.341 kHz. The number of data samples is 185364. All reverberation times for a benchmarked synthetic signal are 0.1 at the center frequency of each third-octave band. The starting center frequency of the third-octave band frequency is 25 Hz and the last center frequency is 4000 Hz. Fig. 2 shows a benchmarked synthetic signal with reverberation time of 0.1 Acoustic decay curves at the third-octave band frequencies for this signal are shown in Fig. 3. Horizontal

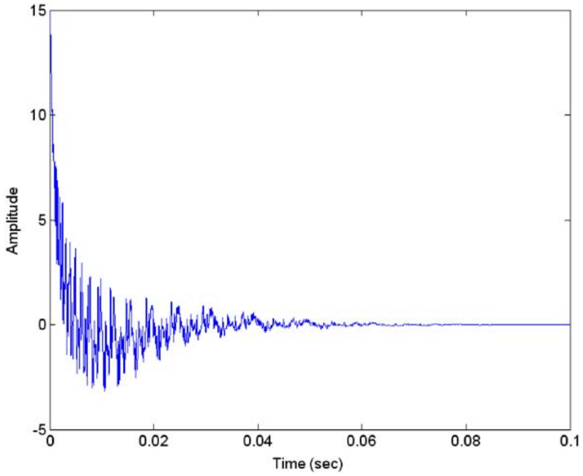


Fig. 2. Benchmarked synthetic signal with reverberation time of 0.1.

axis in Fig. 3 is the center frequency of the third octave band. The first row in Fig. 3 shows the acoustic decay curve filtered by the third-octave band pass filter bank. The second row in Fig. 3 shows the acoustic decay curve filtered by the third-octave band wavelet filter bank. These two rows show acoustic decay curves before backward integration. The third row shows the comparison between the acoustic decay curves filtered by the third-octave band pass filter bank and those by the third-octave band wavelet filter bank after backward integration. According to these results, severe distortions in the acoustic decay curves between 80 and 250 Hz are shown when the third-octave band pass filter is applied. For a detailed analysis, the reverberation times using both filter banks are measured and compared. Fig. 4(a) shows the comparison of reverberation times. The solid line is the result measured by the third-octave wavelet filter bank. The other solid line with circles is the result measured by the third-octave band pass filter bank. Above 315 Hz, it is difficult to find differences between both lines. The values of BT product associated with these reverberation times are shown in Fig. 4(b). Above 315 Hz, it is still difficult to find a difference in both lines. However, the difference in both lines is shown in Fig. 5, which is in the zoomed-in version of Fig. 4(a). According to these results, the difference of both lines is not exactly found above 800 Hz. There is a difference in both lines even between 315 and 630 Hz. These results correspond very well with that result as shown in Fig. 4(b) since the value of BT is higher than 16 only above 800 Hz. At center frequencies between 315 and 630 Hz, the value of BT is still less than 16. Therefore, all reverberation times measured by the third-octave band pass filter are not 0.1 at the center frequencies below 800 Hz. However, all reverberation times measured by using the third-octave wavelet filter bank are 0.1 at center frequencies above 200 Hz as shown in Fig. 5. At center frequencies above 250 Hz, the values of the BT product are higher than 4 as shown in Fig. 4(b). These results correspond to the requirement of the BT product as discussed in Section 2. For further confirmation of this result, reverberation times and BT products for the two more synthetic signals are measured and plotted in Figs. 6(a) and (b), respectively. The reverberation times used for two more synthetic signals are 0.05 and 0.4, respectively. Comparing the three lines in Figs. 6(a) and (b), the reverberation times are exactly 0.4, 0.1 and 0.05,

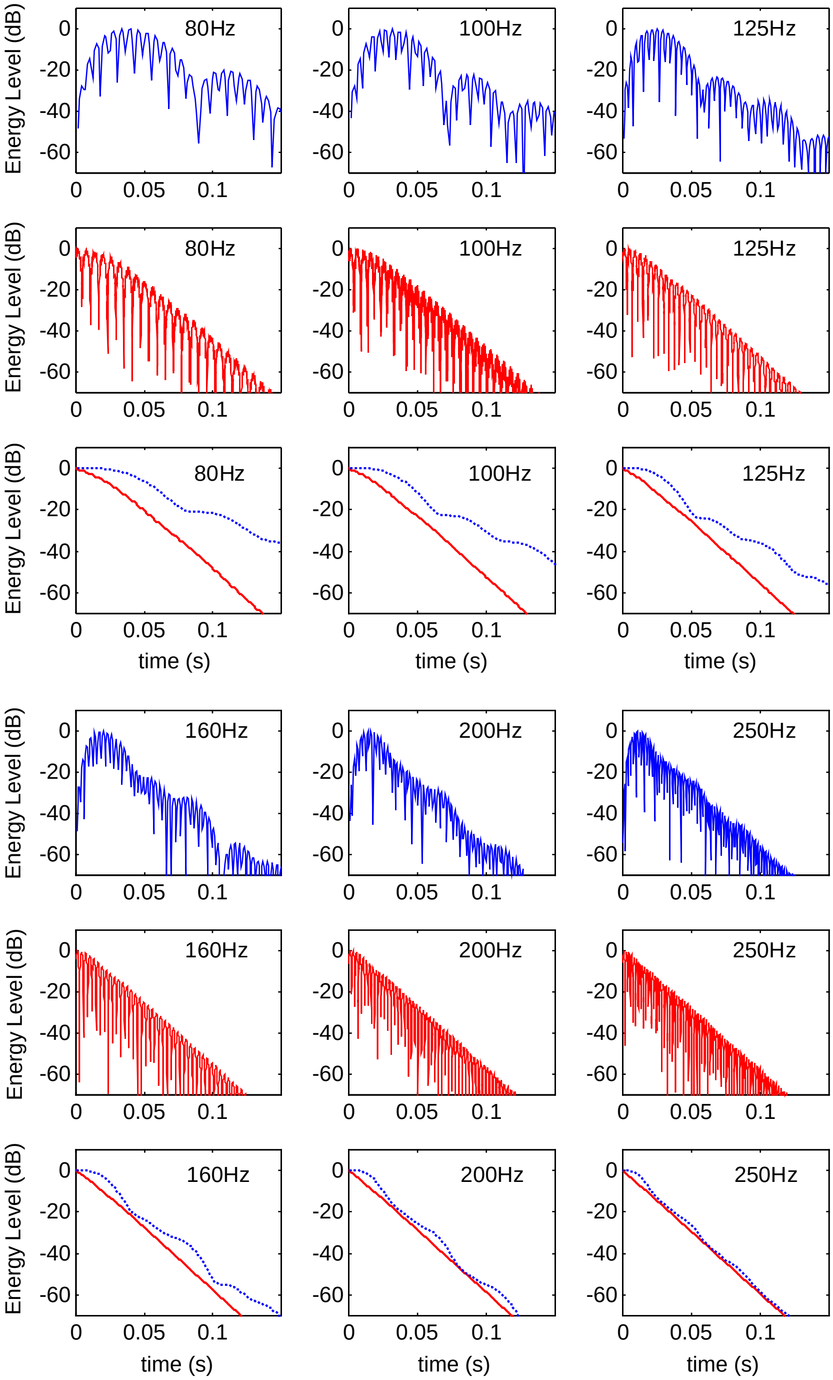


Fig. 3. Comparison of acoustic decay curves calculated by applying the band pass filter bank and the wavelet filter bank to the exponential decay function with the frequency from 80 to 1000 Hz. First row is calculated by using the third-octave band pass filter. Second row is calculated by using the third-octave wavelet filter. The last row is a comparison between acoustic decay curves calculated by the back integration method which is suggested by Schroeder. ——, band pass filter; - - - -, wavelet filter.

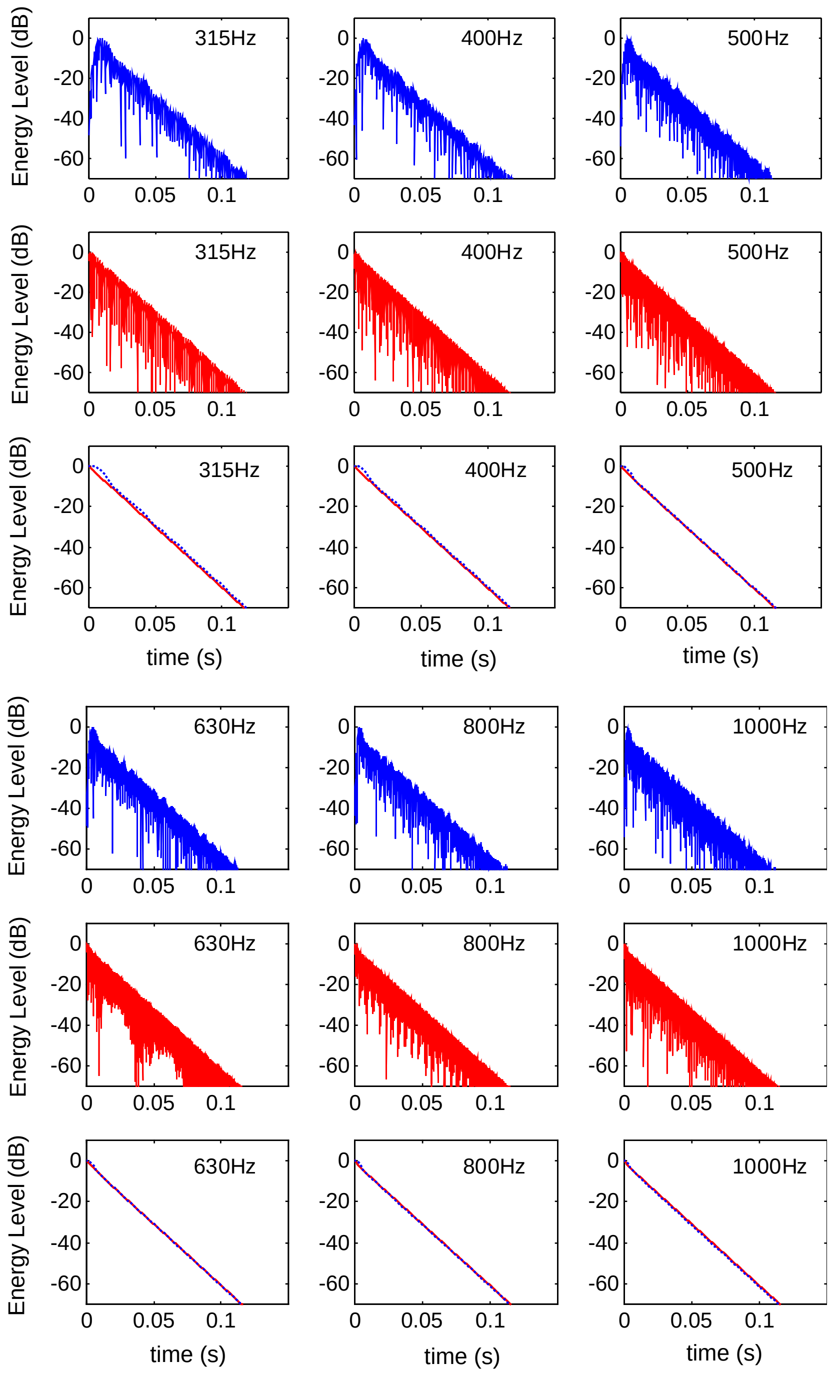
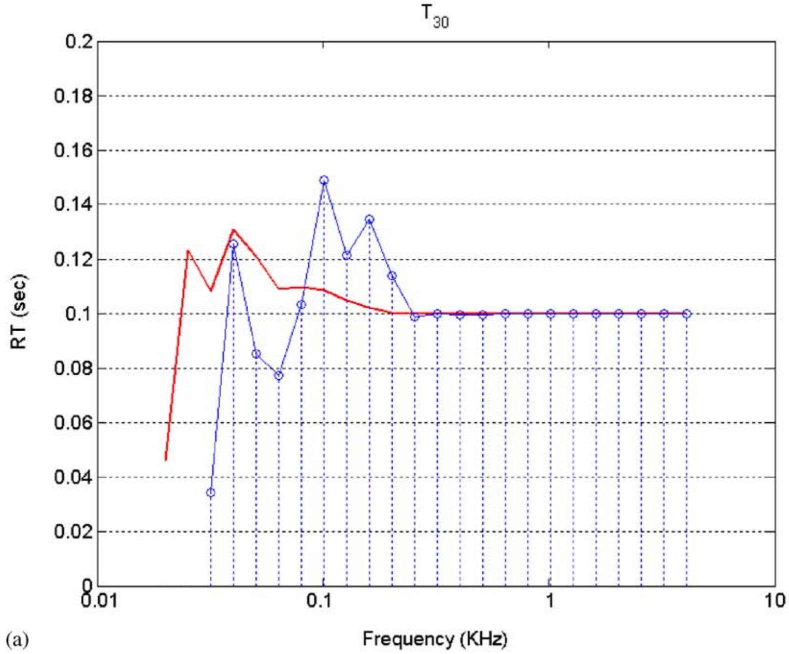
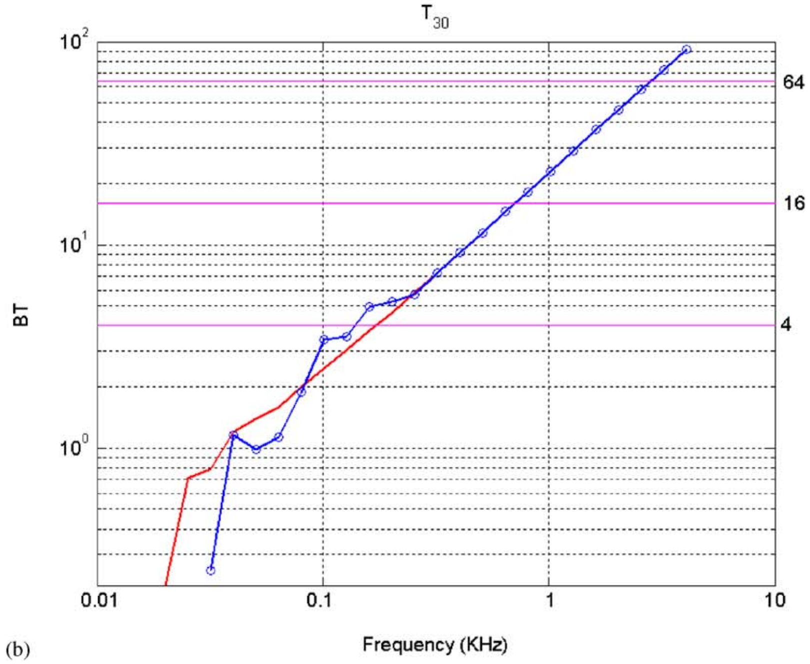


Fig. 3 (*continued*).



(a)



(b)

Fig. 4. Reverberation times and values of BT product for a synthetic signal with reverberation time of 0.1 measured by the wavelet filter bank (——) and by band pass filter bank (— ○ —). (a) Reverberation times and (b) BT product.

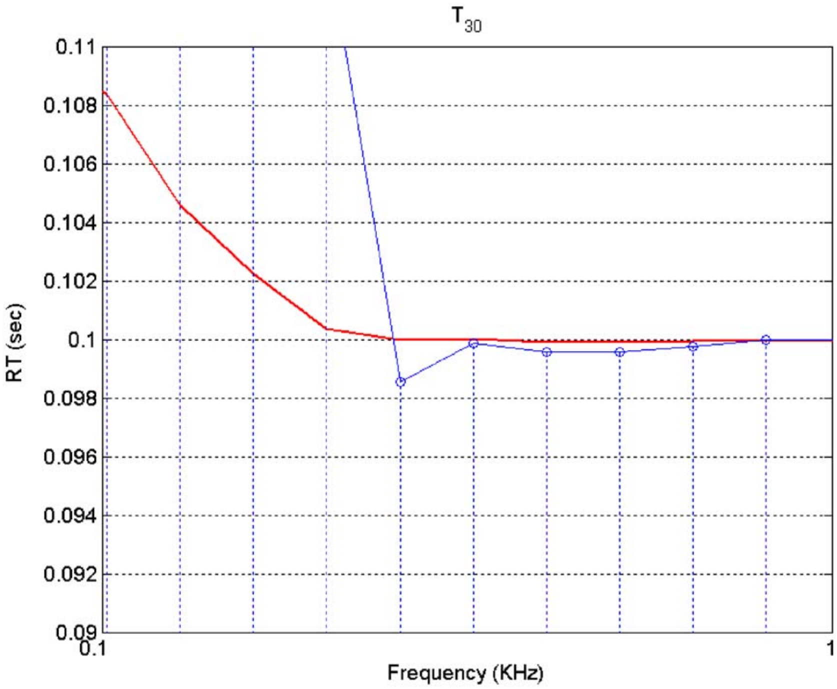


Fig. 5. Zoomed-in version of reverberation times as shown in Fig. 4(a).

respectively, at the frequencies where the value of BT is higher than 4. Therefore, it is justified to say that the wavelet filter bank is a more useful method than the band pass filter bank for the measurement of the reverberation time of the acoustic room with low value of BT product.

4. Reverberation time for an acoustic room

The impulse response of a real acoustic room under test is shown in Fig. 7. For the measurement of the impulse response of the room, a pistol shot is used for excitation of the room [9]. The acoustic room is designed for listening for car sounds. The reverberation times are obtained by using both the third-octave band pass filter bank and the wavelet filter bank. The results are plotted in Fig. 8(a). The horizontal axis is the center frequency of the third-octave band. Above the center frequency of 250 Hz, reverberation times calculated by both filter banks are the same value. At these center frequencies, the reverberation times are around 0.4. The values of BT product are also calculated and shown in Fig. 8(b). Above the center frequency of 250 Hz, the value of BT is higher than 16. At the center frequency 160 and 200 Hz, although the BT product is slightly higher than 16, the reverberation time obtained by the band pass filter is not possibly true since, at these center frequencies, the value of BT is near to the limit value 16. The reverberation times obtained by the wavelet filter bank are definitely true at the center frequency above 63 Hz because the value of BT is higher than 4 above this center frequency. Therefore, it is

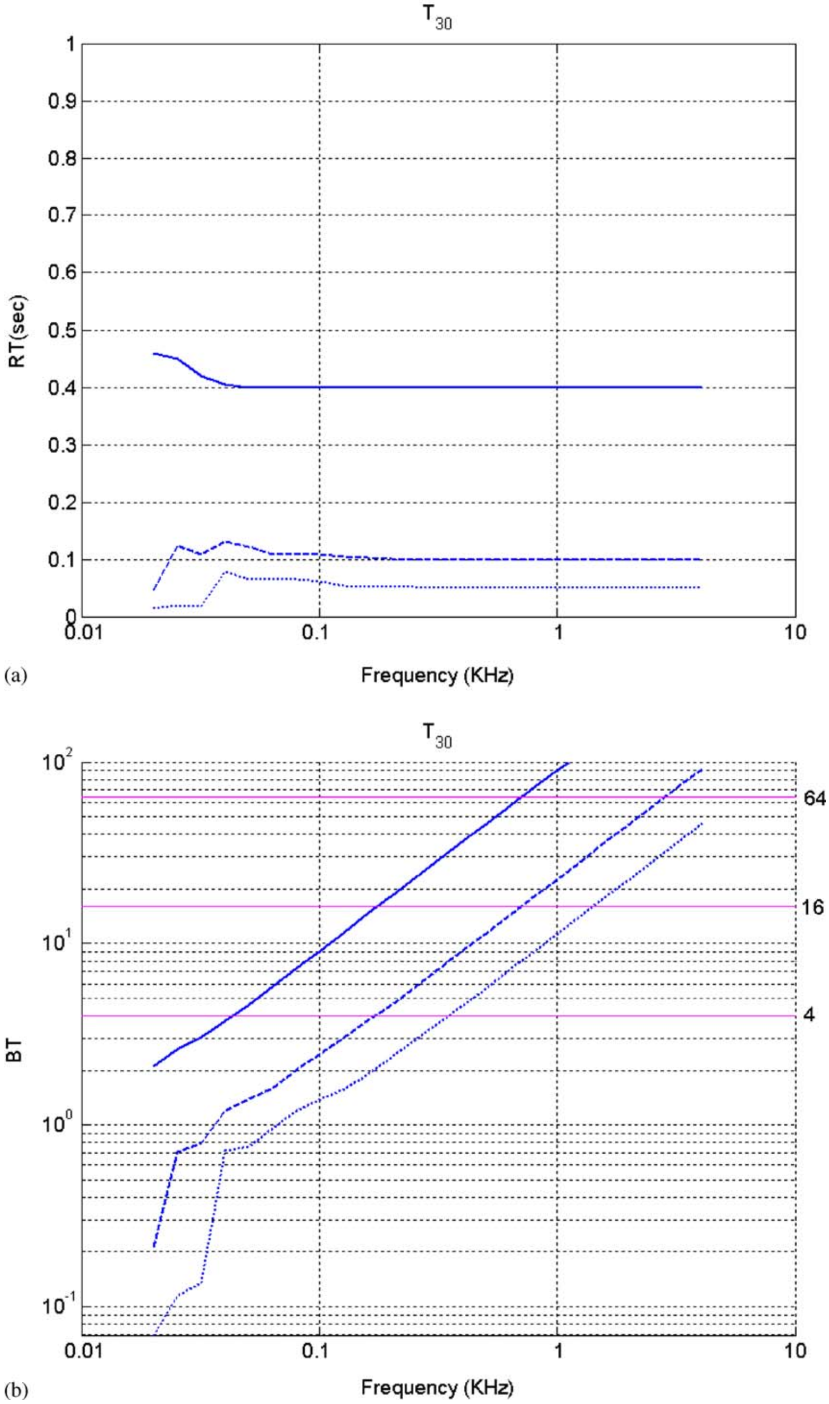


Fig. 6. Reverberation times and values of BT product for three synthetic signals with reverberation times of 0.4, 0.1 and 0.05 by using only wavelet filter bank. (a) Reverberation times and (b) BT product. $RT = 0.4$ (——), $RT = 0.1$ (- - - - -), $RT = 0.05$ (· · · · · ·).

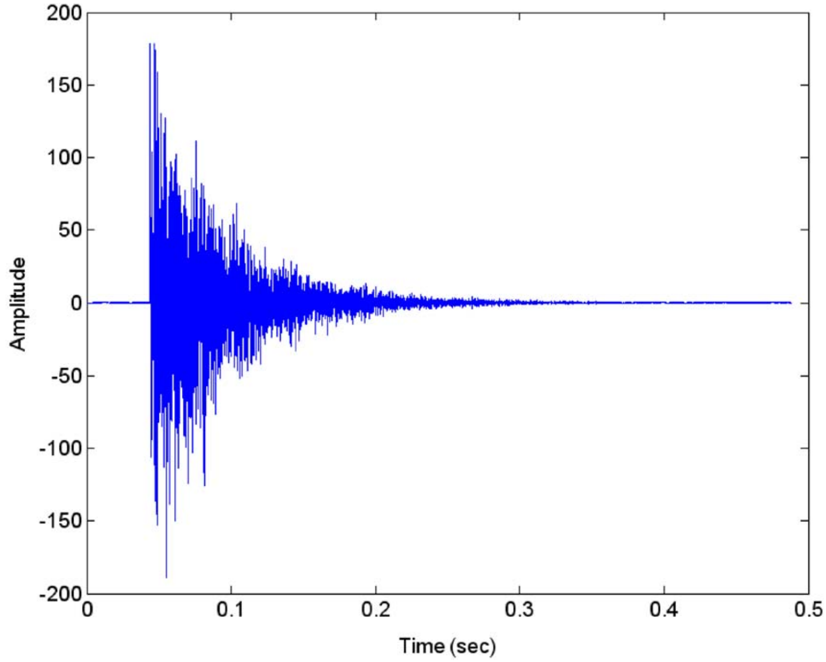


Fig. 7. Impulse response of a real acoustic room for listening for car sounds.

possible to measure the reverberation times with accuracy even at the center frequencies between 63 and 200 Hz by using the wavelet filter bank. However, the reverberation times measured by using the traditional band pass filter at these frequencies include severe errors.

5. Conclusions

In general, the traditional band pass filter bank has measured reverberation times for a long time. However, it is often difficult to measure them when reverberation times are very short because the BT product is less than 16. In order to overcome this problem, in this study, the new wavelet filter bank was applied to the measurement of short reverberation time. In order to facilitate the interpretation of this work, three impulse responses of an acoustic room were synthesized. The short reverberation times for synthetic signals are 0.4, 0.1 and 0.05. The reverberation times measured by using the wavelet filter bank correspond to these reverberation times (0.4, 0.1 and 0.05) exactly at the center frequencies where the BT product is higher than 4. However, the reverberation times obtained by using the traditional band pass filter do not correspond to these reverberation times exactly until the BT product is higher than 16. Reverberation times for a real acoustic room were also exactly measured by using the wavelet filter bank at the center frequencies where the BT product is higher than 4. The reverberation time of this room is around 0.4 at center frequencies above 63 Hz.

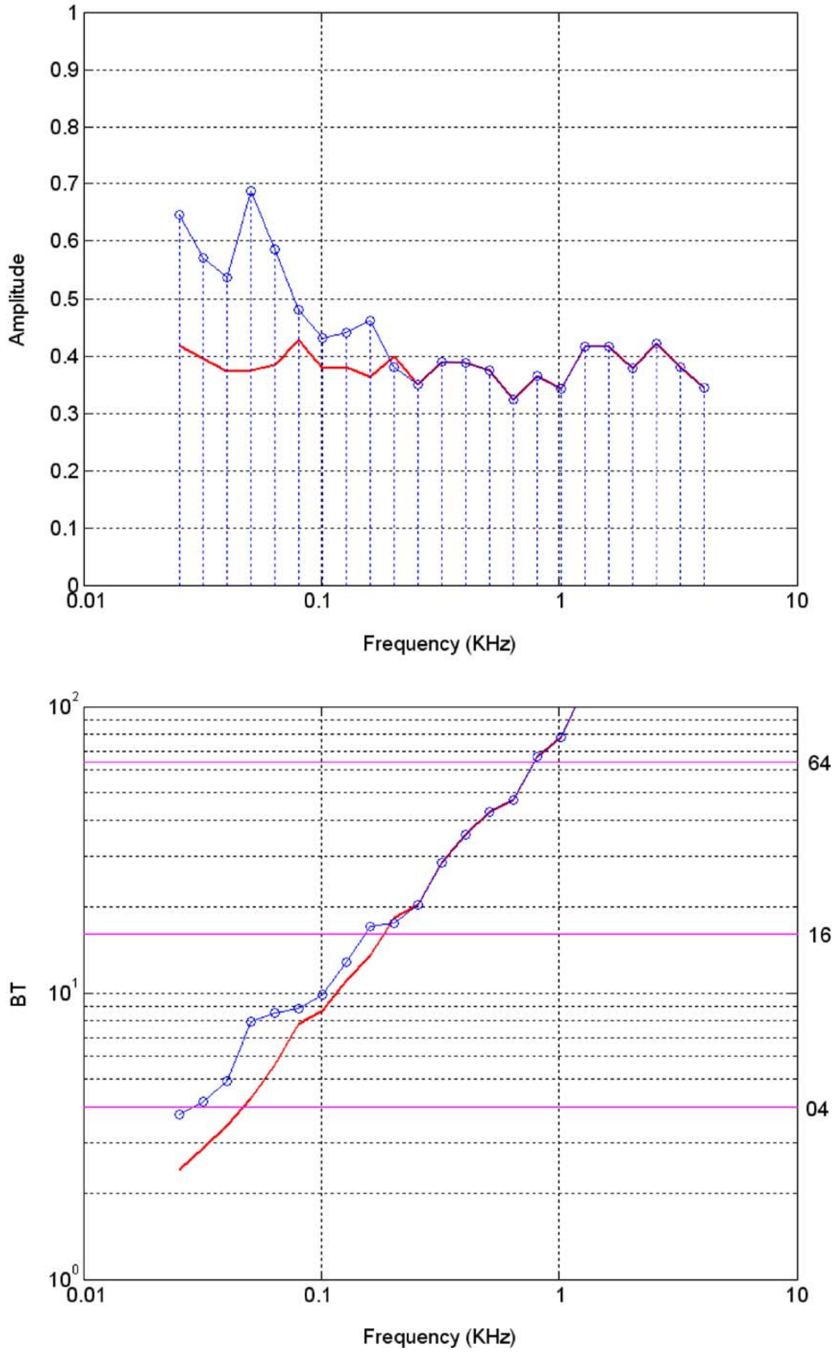


Fig. 8. Reverberation times and values of *BT* product for the impulse response of a real acoustic room measured by the wavelet filter bank (——) and by band pass filter bank (— ○ —). (a) Reverberation times and (b) *BT* product.

Acknowledgements

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