Measurement of Short Reverberation Times at Low Frequencies Using Wavelet Filter Bank

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In room acoustics, reverberation time is an important acoustic parameter. However, it is often difficult to measure short reverberation times at low frequencies with a traditional band pass filter bank if the product of filter bandwidth (B) and reverberation time (T) is small. It is well known that the minimum permissible product of bandwidth and reverberation time of the traditional band pass filter is at least 16. This strict requirement makes it difficult to measure short reverberation times of an acoustic room at low frequencies exactly. In order to reduce this strict requirement, in the previous paper, the wavelet filter bank was developed and the minimum permissible product of bandwidth and reverberation time was replaced with 4. In the present paper, it is demonstrated how the short reverberation times of an practical room at low frequencies are successfully measured by using the wavelet filter bank and the results are compared with the traditional method using a band pass filter bank.

Key Words : Reverberation Times, Room Acoustics, Wavelet Filter

1. Introduction

Before Schroeder (1965) proposed the backward integrated impulse response method in 1965 for determining reverberation times, the most common method in use had been traditional interrupted noise method utilizing the ensemble averaged acoustic decay curve. Unfortunately, the interrupted noise method is a very time-consuming procedure, as Kuttruff (1991) pointed out.

The backward integrated impulse response method does not suffer from the time-consumption procedure. However, there are two serious measurement errors : one due to background noise and the other to the filtering process. Kurer and Kurze (1967) touched on the subject and Jacobsen (1978a) studied it in detail. Jacobsen suggested that the product (BT) of bandwidth (B) of band pass filter and reverberation time (T) of the room under test has to 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 at low frequencies using a band pass filter of particular acoustic rooms, such as talk-studios in broadcasting (Rasmussen and Henriksen, 1991) and the compartments of passenger cars (Ebbit and Rauf, 1996) since they have short reverberation times.

To overcome this problem, Jacobsen suggested a different technique: time-reverse decay measurement (Jacobsen, 1987b). The time-reverse decay method is applied to the evaluation of reverberation time of the new studio of the Danish Broadcasting Corporation (Rasmussen and Henriksen, 1991). However, this method uses long time delayed time acoustic decay curves for the evaluation of reverberation times. Therefore, very short reverberation times cannot be measured in one third-octave band by using traditional measuring techniques. Recently, Lee (2001a) suggested a new method, which is called the wavelet transform-based method. In that paper, the method determining only acoustic decay curves without

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distortions was presented and that method replaces the inequality $BT<16$ with $BT<4$ without the delay effect of acoustic decay curves. In the present paper, the new wavelet transform-based method has been used for the measurement of very short reverberation times of an practical acoustic rooms, and the results are compared with the traditional method using a band pass filter bank. In this approach, two synthetic signals and one signal measured in the listening room for sound quality analysis of passenger cars are used for impulse responses of acoustic rooms. Between two synthetic signals, one is considered with background noise the other one is not. The reverberation times of both synthetic signals are given at whole frequency bands. The reverberation times are calculated through three methods: the ear decay curve (EDT), T_{20} and T_{30}. These known reverberation times are well evaluated by using the wavelet transform-based method at even low even frequency ranges where the value of BT is less than 16 but higher than 4. Finally, wavelet transform-based method is successfully applied to the evaluation of short reverberation times at low frequencies of the listening room for sound quality analysis.

2. Influence of Filters

2.1 Third-octave band pass filter

In the present paper, the band pass filter used for the measurement of reverberation time is the third-octave band pass filter recommended by ANSI1. 11-1986 and IEC225-1966. The bandwidths B of these filters are the same but filter shapes are different, each having different slopes in dB per octave. In many applications it is desirable that the third-octave band pass filter is as selective as possible. The type of the third-octave band pass filter used throughout this paper is the Order 3 Butterworth filter designed by using MATLAB, which is a family of Class III third-octave band pass filters recommended by ANSI1. 11-1986. Its attenuation slope is around 50dB per octave. Figure 1 shows a constant-Q (quality factor) third-octave band pass filter bank, which is going to be used throughout this paper.

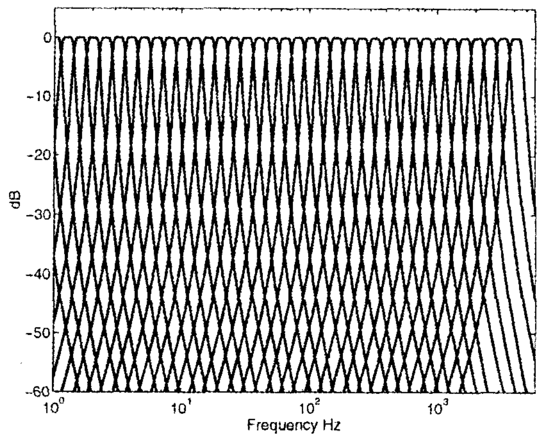


Fig. 1 The third-octave band pass filter bank

2.2 Third-octave wavelet filter

The wavelet transform-based method used throughout this paper is based on continuous wavelet transform. The mathematical definition of a continuous wavelet transform of a signal $x(t)$ is defined by (Onsay and Haddow, 1994):

$$W_x^{\psi}(a, b)=\int_{-\infty}^{+\infty} x(t)\, \psi_{a,b}^{*}(t)\, dt \tag{1}$$

$$\psi_{a,b}(t)=\frac{1}{\sqrt{a}}\, \psi\left(\frac{t-b}{a}\right),\ a>b\in\mathcal{R} \tag{2}$$

where a, $b\in\mathcal{R}$ and $a\in 0$. The function $\psi_{a,b}(t)$ is obtained by applying the operations of shifting (b-translation) in the time domain and scaling in the frequency domain (a-dilation) to the mother wavelet. The mother wavelet used throughout this paper is the Morlet wavelet (Teolis, 1998),

$$\psi(t)=\frac{1}{\sqrt{\pi B}} e^{j\omega_0 t-(t^2/B)}, \tag{3}$$

where ω_0 is the center frequency of the "mother wavelet" and B is the bandwidth defined as the variances of the Fourier transform $\Psi(f)$ of the Morlet wavelet (Lee, 2000b)

$$B=\int_{-\infty}^{+\infty} f^2 \Psi^{*}(f)\, df \tag{4}$$

The relationship between the scale parameter a and frequency $\omega=2\pi f$ is given by

$$a=\frac{\omega_0}{\omega} \tag{5}$$

where ω_0 is the center frequency of the "mother wavelet" (see Eq. (2)). From a signal processing

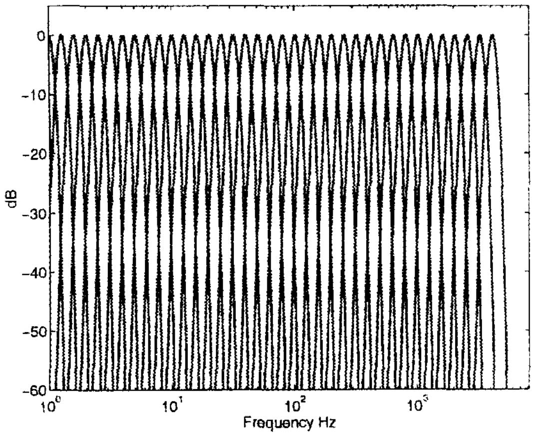


Fig. 2 The third-octave band wavelet filter bank

point of view, a wavelet basis generates a constant-Q octave-band or octave band filter bank structure (Lee, 2001c). Therefore, the third-octave band filter bank can be generated. It is called "third-octave wavelet filter bank" throughout this paper and is plotted in Fig. 2. In this graph, the logarithmic scale of the coordinate allows us to view the constant-Q characteristics of the wavelet basis more clearly.

2.3 Influence of both filters on acoustic decay curves

Let's consider a room under test as a linear system of which the impulse response is $h(t)$. For the measurement of the impulse response of the room, one method is to excite the room by using impulse input sources such as pistol shots (Vorlander and Bietz, 1994), and then the output response of the microphone is the impulse response of the room. The reverberation time T is defined as the time required for 60dB attenuation of energy level of acoustic decay curves (Kuttruff, 1991). In order to get the acoustic decay curves at each third octave band center frequency, the impulse response should be passed through a third octave band pass filter bank or third-octave band wavelet filter bank. The bandwidth B of the third octave band filter is different at each center frequency. At low frequencies, the bandwidths are narrow, whereas they are wide at high frequencies. Therefore, the values of BT are smaller at low frequencies than that at high frequencies. In

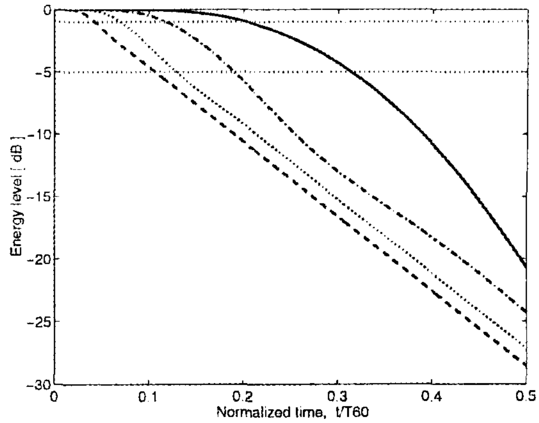


Fig. 3 Acoustic decay curves calculated by applying to the third-octave band pass filter bank to the exponential decay function oscillating with frequency 125 Hz; $BT_{60}=4$ (———), $BT_{60}=8$ (–·–·–), $BT_{60}=16$ (·········), $BT_{60}=32$ (– – – –)

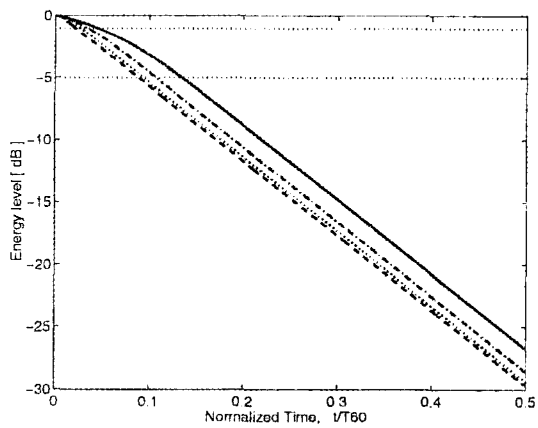


Fig. 4 Acoustic decay curves calculated by applying to the third-octave band wavelet filter bank to the exponential decay function oscillating with frequency 125 Hz; $BT_{60}=4$ (———), $BT_{60}=8$ (–·–·–), $BT_{60}=16$ (·········), $BT_{60}=32$ (– – – –)

order to compare the influence of filters between the band pass filter bank and the wavelet filter bank, the acoustic decay curves are calculated with the exponentially decaying ideal impulse response

$$h_t(t) = \begin{cases} e^{t/2\lambda} \cos \omega_i t & \text{for } t>0 \\ 0 & \text{elsewhere} \end{cases} \quad (6)$$

where $T=6\ln(10)\lambda$ and ω_i is 125 Hz center frequency of the third-octave band filters. The results are plotted in Fig. 3 for band pass filter and Fig. 4 for wavelet filter, respectively. From these results, the conclusions listed in table 1 can be obtained (Lee, 2001a).

3. Reverberation Time Measurement

This section explains how to measure the short reverberation times at low frequencies by using the wavelet transform-based method. In order to explain the method, the listening room for automotive sound quality analysis is adopted. This room has short reverberation time. In order to facilitate the interpretation of the reverberation time resulting from an impulse response of the listening room, the analysis is first demonstrated on benchmarked synthetic signals.

3.1 Benchmark signal

3.1.1 Noise-free synthetic signal

The benchmarked synthetic signal used for impulse response of a room consists of the sum of ideal decay function in Eq. (6). The mathematical expression of the impulse response is given by

$$h(t)=\sum_{i=1}^{L}h_i(t) \tag{7}$$

$$h_i(t)=\begin{cases} e^{t/2\lambda}\cos\omega_i t & \text{for } t>0 \\ 0 & \text{elsewhere}\end{cases} \tag{8}$$

where $T=6\ln(10)\lambda$ and ω_i is the i-th center frequency of the third-octave band. The ideal decay signal $h_i(t)$ at each third octave center frequency ω_i is made with sampling frequency of 46.341 kHz. The number of data samples is 185364. The number of third-octave bands used for synthetic impulse response (L) is 24. One is used for reverberation times at each third-octave band center frequency. The starting center frequency of the third-octave band frequency is 25 Hz and the last center frequency is 4000 Hz. In Fig. 5(a) and Fig. 6(a), the synthetic impulse response is plotted. In order to compare the influence of both wavelet filters bank and band pass filter bank, the reverberation time T and the value of BT product are calculated, respectively,

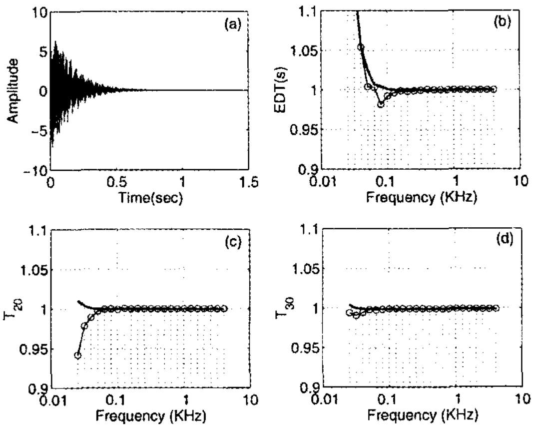


Fig. 5 Comparison between the reverberation times obtained by the third octave band wavelet filter bank (———) and the reverberation times obtained by the third octave band pass filter bank (—o—) for synthetic impulse response signal (a) Synthetic impulse response without background noise, (b) Reverberation times through EDT, (c) Reverberation times through T_{20} and (d) Reverberation times through T_{30}

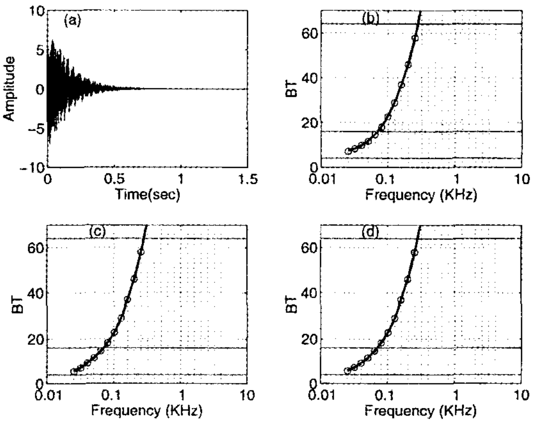


Fig. 6 Comparison between the value of BT product obtained by the third octave band wavelet filter bank (———) and the value of BT product obtained by the third octave band pass filter bank (—o—). (a) Synthetic impulse response without background noise, (b) BT product calculated through EDT, (c) BT product calculated through T_{20} and (d) BT product calculated through T_{30}

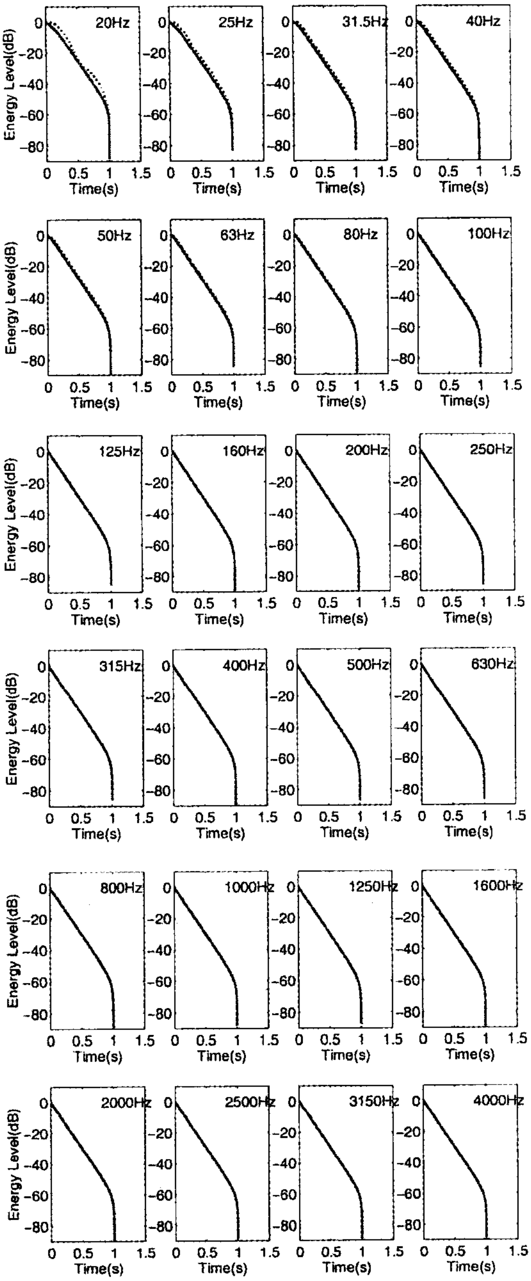


Fig. 7 Comparison between acoustic decay curves calculated by applying the third-octave band wavelet filter bank (———) and acoustic decay curves calculated by applying the third-octave band pass filter bank (·········)

and plotted as shown in Fig. 5 and Fig. 6. Reverberation times as shown in Fig. 5(b), (c) and (d) are obtained by evaluating three methods *EDT*, T_{20} and T_{30} and the values of *BT* product corresponding to these reverberation times are plotted in Fig. 6(a), (b) and (c). The *EDT* is defined with an evaluation range from -1dB to -10dB of acoustic decay curve as shown in Fig. 7.

Similarly, T_{20} and T_{30} are defined with an evaluation range from -5dB to -25dB and range from -5dB to -35dB of acoustic decay curves, respectively. It is natural that the effect of background noise is significant for measuring the reverberation times. In this section, in the condition of noise-free background, reverberation times are evaluated through linear regression of acoustic decay curves as shown in Fig. 7. Initially, acoustic decay curves, as shown in Fig. 7, are obtained by backward integrating the synthetic impulse response filtered by wavelet filter bank or band pass filter bank. In Fig. 7, the solid line is the acoustic decay curve passing through the wavelet filter bank and the dotted line is that passing through the band pass filter bank. There is a difference between the solid line and the dotted line at center frequencies under 80 Hz. This difference induces the difference between the reverberation times obtained by using both the wavelet filter bank and the band pass filter bank. In Fig. 5(b), (c) and (d), the dotted vertical lines display the center frequencies of the third octave band from 25 Hz to 40 kHz, the solid bold line illustrates the reverberation time obtained by using the wavelet filter bank, and the circles line is that obtained by using the band pass filter bank. According to these results, if the wavelet filter bank is applied, reverberation times evaluated through both T_{20} and T_{30} are unity at the center frequencies from and above 31.5 Hz. However, for the band pass filter bank, reverberation times calculated through both T_{20} and T_{30} become unity at the center frequencies from and above 80 Hz. Therefore, during measurement of reverberation time by using T_{20} or T_{30} the influence of the wavelet filter is given below 31.5 Hz. The reason for this phenomenon is that the values of BT at the center frequencies under 31.5 Hz are less than 4, as shown in Fig. 6(c) and (d), required in Table 1. Although the value of *BT* at the center

Table 1 Comparison of the values of the BT required obtaining acceptable decay curve by the third-octave fitter banks

Filter Bank Type	Straight decay line at 5dB below stationary level	Straight decay line at 1dB below stationary level
Band pass filter bank	$BT>16$	$BT>64$
Wavelet filter bank	$BT>4$	$BT>16$

frequency 25 Hz is over 4, it is not true since both T_{20} and T_{30} at the center frequency 25 Hz are larger than unity as shown in Fig. 5(c) and (d) and are overestimated. The influence of the band pass filter used for measurement of reverberation time by using T_{20} or T_{30} is significant below 80 Hz since the value of BT is less than 16, as shown in Fig. 6(c) and (d), required in Table I in this range. Reverberation times evaluated through EDT obtained by using wavelet filter bank are not unity at the center frequencies until 100 Hz as shown in Fig. 5(b) since the values of BT below 100 Hz, as given in Fig. 6(b), are less than 16 required in Table 1. On the other hand, EDT obtained by using the band pass filter bank become unity at the center frequency from and above 315 Hz as shown in Fig. 5(b) since the values of BT in this range, as given in Fig. 6(b), are larger than 64 required in Table 1. When the wavelet filter bank is applied to the evaluation of reverberation times of the synthetic impulse response, the values of BT against the third-octave center frequencies are as shown in Fig. 8(a) in detail. The values of BT using T_{20} and T_{30} increase linearly on the log-log coordinate, but those using EDT increase nonlinearly at low frequencies. Ideally, because reverberation times are all unity, the value of BT should be increased linearly on the log-log coordinate. The reverberation times measured by wavelet filter bank are plotted in Fig. 8(b) in detail. The reverberation times evaluated through T_{20} and T_{30} are all unity except for the range of center frequencies under 25 Hz.

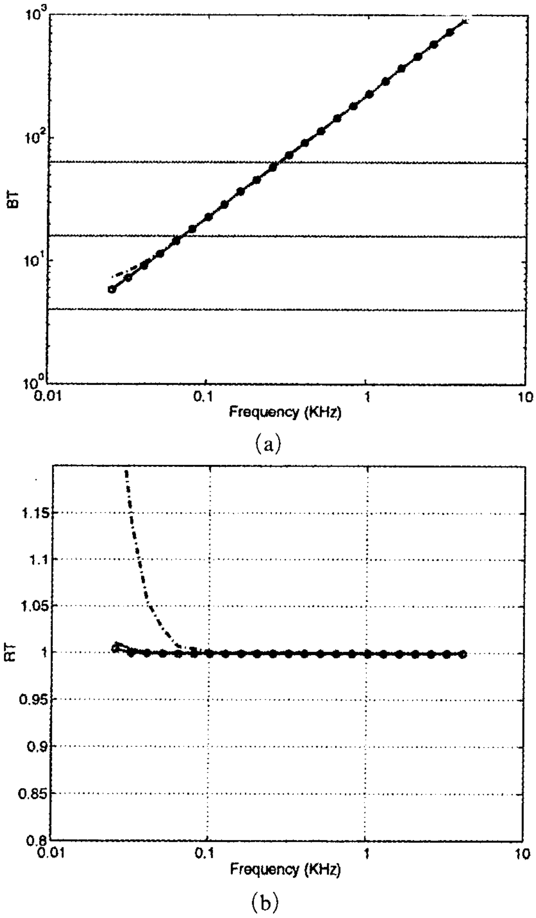
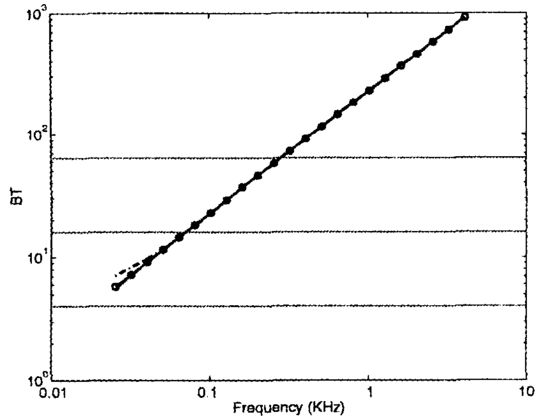
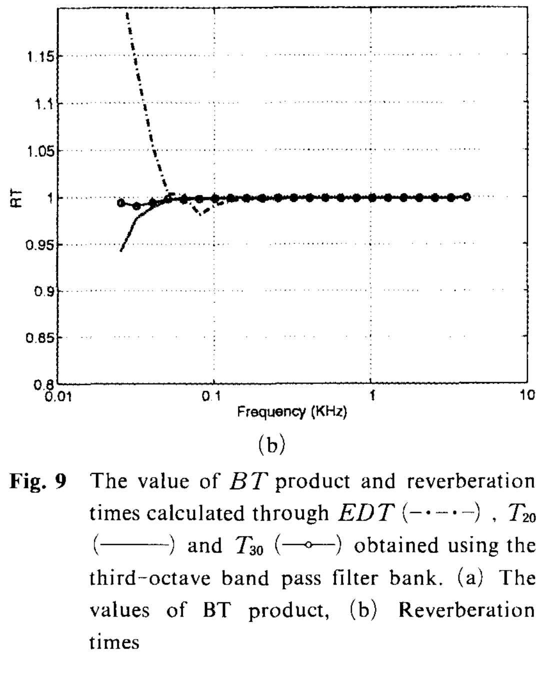


Fig. 8 The value of BT product and reverberation times calculated through EDT (–·–·–), T_{20} (———) and T_{30} (—o—) obtained using the third-octave wavelet filter bank. (a) The values of BT product, (b) Reverberation times

Reverberation times using EDT are unity centered from and over frequencies of 100 Hz. When the band pass wavelet filter bank is applied to the evaluation of reverberation times of the synthetic impulse response, the values of BT against the third-octave center frequencies are as shown in Fig. 9(a) in detail. The values of BT using T_{20} and T_{30} increase in linear line on the log-log coordinate at the center frequencies from and over 80 Hz, but that using EDT increase linearly at the center frequencies from and over 315 Hz. The corresponding reverberation times are shown in



(a)



(b)

Fig. 9 The value of BT product and reverberation times calculated through EDT (–·–·–), T_{20} (———) and T_{30} (—o—) obtained using the third-octave band pass filter bank. (a) The values of BT product, (b) Reverberation times

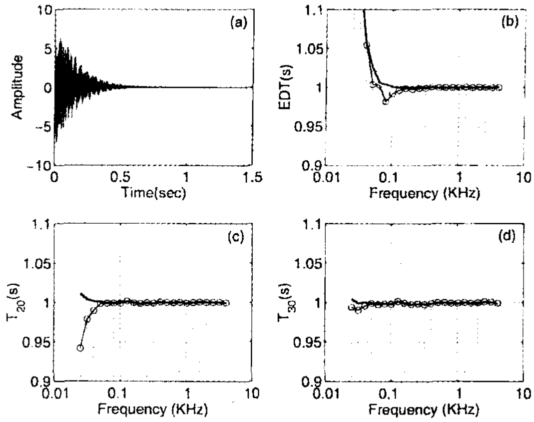


Fig. 10 Comparison between the reverberation times obtained by the third-octave band wavelet filter bank (———) and the reverberation times obtained by the third-octave band pass filter bank (—o—) for synthetic impulse response signal with background noise. (a) Synthetic impulse response with background noise, (b) Reverberation times through EDT, (c) Reverberation times through T_{20} and (d) Reverberation times through T_{30}

Fig. 9 (b) in detail. The reverberation times using T_{20} and T_{30} are unity from and over center frequencies 80 Hz but these using EDT are unity at the center frequencies from and above 315 Hz. Therefore, in order to measure the short reverberation times at the low frequency it is concluded that the measurement of reverberation times using a wavelet filter bank yields more accurate results than that using a band pass filter bank.

3.1.2 Synthetic signal with background noise

The synthetic impulse response with background noise consists of the sum of white noise and noise-free impulse response explained in Eq. (8). According to the literature, in order to reduce the effect of background noise for measurement of reverberation time evaluated through T_{30} it is known that the required signal to noise ratio (SNR) is at least 40dB (Vorlander and Bietz, 1994).

Signal to noise ratio of the synthetic signal used throughout this paper is 41dB. Time history of synthetic impulse response with background noise used throughout this paper is plotted in Fig. 10 (a). The reverberation times evaluated through EDT, T_{20} and T_{30} are estimated by using a similar method discussed in section 1 and results are illustrated in Fig. 10(b) (c) and (d), respectively. According to these results, reverberation times of the synthetic impulse response with background noise are almost same as that of the noise-free synthetic impulse response in section 1. The main reason for these results is the fact that the SNR of the synthetic signal satisfies the low limit of SNR 40dB. Therefore, if the SNR of impulse response of the small room with short time reverberation is sufficient, it is again concluded that the measurement of reverberation time by using the wavelet filter bank is more accurate than that using the band pass filter bank at the low frequencies.

3.2 Application

A newly developed wavelet transform-based method has been applied to the measurement of reverberation time of the listening room for automotive sound quality analysis. The room has volume of $4 \times 4.4 \times 3$ m^3. A 6-mm pistol was used for impulse excitation of the room because a pistol improves the SNR at low frequencies (Rasmussen and Henriksen, 1991). The room was treated with acoustic materials since a passenger car compartment has short reverberation time (Ebbit and Rauf, 1996). The impulse response of the room was measured by Bruel & Kjær 4189 type microphone and 01dB-Stell SYMPHONIE systems. The time history of impulse response of the room under test is plotted in Fig. 11(a).

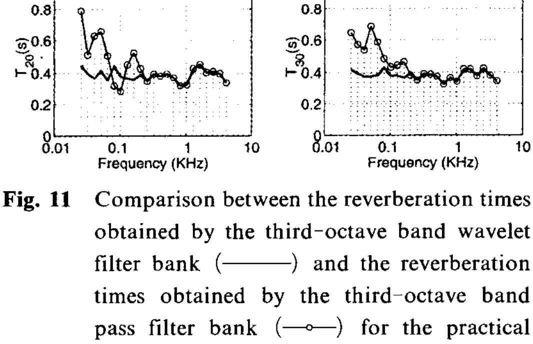


Fig. 11 Comparison between the reverberation times obtained by the third-octave band wavelet filter bank (———) and the reverberation times obtained by the third-octave band pass filter bank (—○—) for the practical impulse response of the listen room for automotive sound quality analysis. (a) Synthetic impulse response with background noise, (b) Reverberation times through EDT, (c) Reverberation times through T_{20} and (d) Reverberation times through T_{30}

Reverberation times of this room are estimated and plotted in Fig. 11(b), (c) and (d). The values of BT product associated with these reverberation times are also shown in Fig. 12(b), (c) and (d). In the graphics, the solid bold lines are related to the wavelet transform-based method, and the narrow line with circles is related to the band pass filter. The acoustic decay curves used for measurement are provided in Fig. 13. Again, the solid bold lines are related to the wavelet transform-based method and dotted lines are related to the method using the band pass filter in the graphics. In the acoustic decay curves as shown in Fig. 13, it is observed that the SNR is enough for measurement of the reverberation times evaluated through T_{30} since the SNR is over 45dB. It is also observed that the effect of the band pass filter is severe at center frequencies under 200 Hz since the values of BT corresponding to these frequencies, as shown in Fig. 12(b), (c) and (d), are less than the low limit 16.

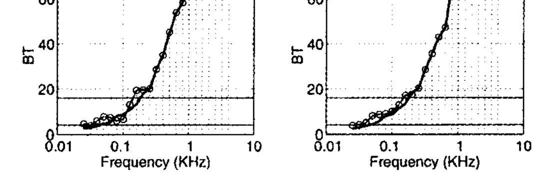


Fig. 12 Comparison between the value of BT product calculated by the third-octave band wavelet filter bank (———) and the value of BT product calculated by the third-octave band pass filter bank (—○—) for the practical impulse response of the listening room for the sound quality analysis of automotive: the third-octave band wavelet filter bank. (a) Synthetic impulse response with background noise, (b) Reverberation times through EDT, (c) Reverberation times through T_{20} and (d) Reverberation times through T_{30}

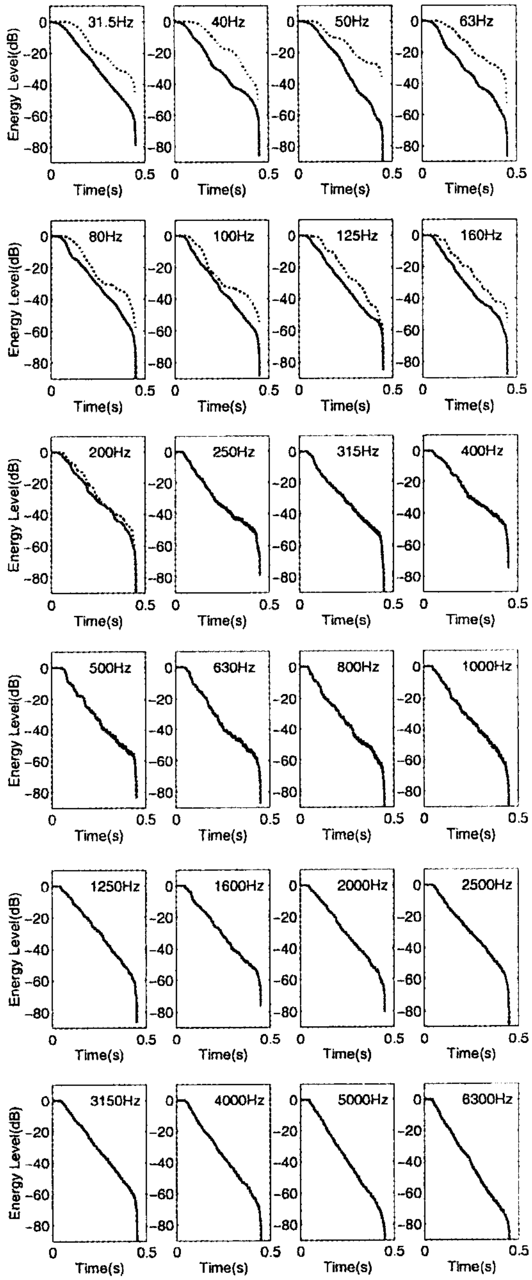


Fig. 13 Comparison between acoustic decay curves calculated with application of the thirdoctave band wavelet filter bank (———) and acoustic decay curves calculated with application of the third-octave band pass filter bank (·········)

However, the effect of wavelet filter bank is given at the center frequencies under 50 Hz. The values of BT corresponding to these frequencies, as shown in Fig. 12(b), (c) and (d), are less than the low limit 4. Therefore, it is concluded that, in order to measure the reverberation time of this room with accuracy at the center frequencies from 50 Hz to 160 Hz, the wavelet filter bank should be applied instead of the traditional band pass filter. These results are well explained with reverberation times as given in Fig. 11(c) and (d). According to these results, at the center frequencies under 200 Hz, reverberation times evaluated through T_{20} and T_{30} by using a band pass filter are very unstable and over-estimated since the BT is less than 16 as shown in Fig. 12(c) and (d). However, reverberation times estimated through T_{20} and T_{30} by using a wavelet filter bank are unstable and over-estimated at the center frequencies under 80 Hz since the BT is less than 4.

Reverberation times evaluated through EDT are plotted in Fig. 11(b). In this graphic, reverberation times evaluated by a using wavelet filter bank are different from reverberation times evaluated by using a band pass filter bank at center frequencies under 1000 Hz. In this frequency region, the value of BT is less than 64 as shown in Fig. 12(b). Therefore, the wavelet transform-based method is more accurate than the traditional band pass filter for the measurement of short reverberation times of this listening room at center frequencies between 50 Hz and 160 Hz.

4. Conclusions

The wavelet transform-based method and the band pass filter-based method are compared for the measurement of short reverberation times of a practical acoustic room. In order to do this, two synthetic impulse responses and an impulse response of practical acoustic room are adopted.

Through analysis of the signals, it is identified that the limits of BT product are important and reasonably well applied to the estimate of short reverberation times not only of the synthetic signals but also the impulse responses of practical acoustic rooms. Therefore, the wavelet transform-based method is better than the traditional band pass filter-based method for the measurement of short reverberation times of acoustic rooms at low frequencies.

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