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Increasing the Accuracy of Reverberation Time Measurement Using Wavelet Thresholding

Denny Hermawato[1,*], Hastuadi Harsa[2]

[1]Acoustic & Vibration Metrology Laboratory, Research Center for Metrology – Indonesian Institute of Sciences (RCM-LIPI), Indonesia
[2]Research and Development Centre, BMKG Jakarta, Indonesia

Abstract Reverberation time measurement is used in building acoustic analysis and determination of acoustic characteristic of a material such as sound transmission loss and sound absorption index. This process measures the time needed for sound to decay 60 dB since the steady sound in the room is switched off. Usually, the reverberation time is estimated from sound decay curve. In the real reverberation time measurement, the smooth sound decay curve is hard to find because the original sound wave combines with reflection sound wave. In this paper, two level Daubechies wavelet transform is performed to filter noise in the sound decay. The applied wavelet thresholding successfully filtered out the maximum and minimum peak in the sound decay curve, therefore the estimation of reverberation time can be done more accurately in high and low frequency region.

Keywords Sound Measurement, Reverberation Time, Wavelet Filter, Daubechies

1. Introduction

Reverberation time is defined as the time in seconds required by sound level to decay 60 dB after a sound source abruptly switch-off [1]. It is used in the sound transmission loss test to determine the STC (Sound Transmission Class) value of partition panel test material [2]. It is also used in absorption coefficient measurement to determine the value of NRC (Noise Reduction Index) of an absorber material [2]. The conventional reverberation time measurement employs many equipment thus make it inefficient for field measurement. The decay of sound level is printed on paper sheet and the value of reverberation time is determined manually using a tool called protractor that convert the sound level decrement slope into time. The determination of reverberation time would spend a lot of time because it is done one by one in 1/3 octave from frequency 125 until 4000 Hz.

In the modern technology, the measurement of reverberation time can be done by utilizing analyzer which has spectrum recording facilities [3]. The 60 dB decrement is estimated directly and simultaneously from the recorded spectrum. Estimation of 60 dB decrement in high frequencies, e.g. above 2500 Hz can be performed easily because the sound decay is nearly linear. But in low frequency region, the decay is not linear; this is because the original sound decay is distorted by reflection sound from the wall. At the microphone, the original sound and reflection sound are summing out together, if the original signal is in phase with reflection signal then the resultant sound level will be higher and if they are out of phase then the resultant signal will be lower than original signal. The resultant signal will create maximum and minimum peak in the sound spectrum makes it hard to estimate the sound decay. Therefore, a post processing to the signal needs to be employed to enhance the accuracy of reverberation time estimation in low frequencies.

Wavelet has been successfully applied in various research areas, such as acoustical signal processing, power production and power electronics, non-destructive testing, chemical processing, stochastic signal processing, image compression, satellite imagery, machine vision, bioinformatic and flow analysis [4]. Donoho [5] proposed a powerful approach for noise reduction called wavelet thresholding and its main applications is for denoising data and images [6, 7, 8]. This paper proposes the application of wavelet thresholding method in the field of acoustic measurement focused on reverberation time measurement.

2. Wavelet Thresholding Methods

Wavelets are mathematical functions that cut up data into different frequency components, and then study each component with a resolution matched to its scale [9]. A wavelet is a kernel function used in an integral transform [4]. The wavelet function (CWT) of a continuous signal x(t) is given by:

$$W_{a,b}(x)=\int_{-\infty}^{+\infty} x(t) \quad _{a,b}(t)dt \qquad (1)$$

with the wavelet function defined by dilating and translating a mother function as:

$$_{a,b}(t)=\frac{1}{\sqrt{h}}\left(\frac{t-g}{h}\right) \quad (2)$$

$\psi(t)$ is being the mother wavelet, **h** the dilation factor and **g** the translation parameter (both being positive number). For practical reasons, these parameters are often discretized leading to the so-called discrete wavelet transform (DWT). After discretization the wavelet function is defined as:

$$_{j,k}(t)=2^{-\frac{j}{2}}\left(2^{-j}t-k\right) \quad (3)$$

As for CWT, the DWT is given by the inner product between signal and wavelet, the result is being a series of coefficients:

$$d_x(j,k)=\langle x, \ _{j,k}\rangle \quad (4)$$

j and k being integer scale and translation factors.

Wavelet thresholding is a technique used to remove random noise and outliers from the signal before reconstruction [10]. Wavelet absolute coefficients larger than a certain specified threshold δ are the ones that should be included in reconstruction. The reconstructed function can be show as:

$$f(t)=\sum_j\sum_k I_{\{|\omega_{j,k}|>\delta\}}\omega_{j,k} \ _{j,k}(t) \quad (5)$$

where $I_{\{|\omega_{j,k}|>\delta\}}$ is the indicator function of this set. This represents a keep or kills wavelet reconstruction. This threshold is a kind of nonlinear operator on the wavelet coefficients vector. This leads to a resultant vector of estimated coefficient $\omega_{j,k}$ to be used in the reconstruction process. The estimated coefficients can be determined from either hard thresholding or soft thresholding. In case of hard thresholding the estimated coefficients will be:

$$\omega_{j,k}=\begin{Bmatrix}\omega_{j,k} & if\,|\omega_{j,k}|>\delta \\ 0 & otherwise\end{Bmatrix} \quad (6)$$

In case of soft thresholding, the estimated coefficients will be:

$$\omega_{j,k}=\begin{Bmatrix}\omega_{j,k}-\delta & if\,|\omega_{j,k}|\geq\delta \\ 0 & if\,|\omega_{j,k}|\leq\delta \\ \omega_{j,k}+\delta & if\ \omega_{j,k}<-\delta\end{Bmatrix} \quad (7)$$

3. Result and Discussion

For the experiments, we will determine reverberation time of a room with the dimension is (4.45 x 4.3 x 3) meter. The shape of the room is rectangular, ceiling, floor and 3 side of the room are made from concrete and particle board is attached in 1 side of the concrete wall. The sound source used in the experiment is pink noise connected to an amplifier and omnidirectional speaker. The sound is capture using microphone type B&K 4191 is used and analyzed using B&K 2144 spectrum analyzer. The real time spectrum analyzer will record the sound spectrum simultaneously in 1/3 octave frequencies. The recorded sound level in the real time analyzer then transferred to the PC for reverberation time analysis. Figure 1 shows an example of the plotted raw data that transferred from real time analyzer.

The wavelet thresholding is applied to the raw data before the computation of reverberation time. The raw data x[n] is decomposed using 2 level wavelet transform with Daubechies D4 mother wavelet. Each level of wavelet transform yields two coefficients those are detail (d) and approximation (a). The method for thresholding that used in this research is hard thresholding. It is done by setting the value of detail value coefficients of the decomposed signal become to zero. The successive process after thresholding is reconstruction of the signal from wavelet detail and approximation coefficients value. Overall process of the developed method can be shown in Figure 2.

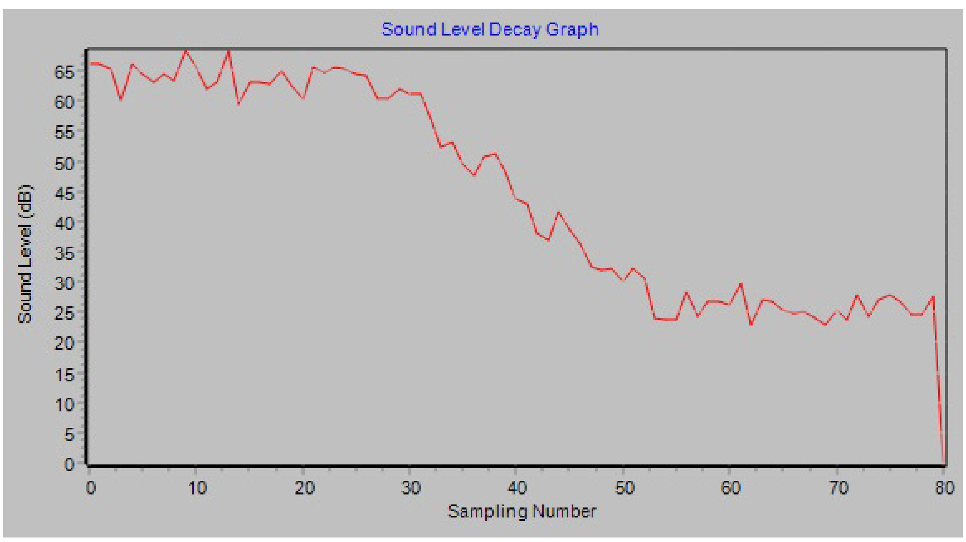

Figure 1. Plotted sound level data at frequency 160 Hz

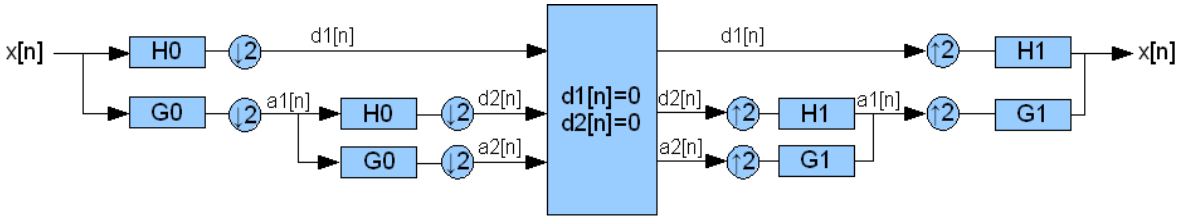

Figure 2. Wavelet thresholding algorithm on the raw data.

Daubechies D4 mother wavelet has four dilation (h) and scaling (g) coefficients. For the decomposition process the dilation coefficients are:

$$h_0 = \frac{1+\sqrt{3}}{4\sqrt{2}} \qquad h_1 = \frac{3+\sqrt{3}}{4\sqrt{2}}$$

$$h_2 = \frac{3-\sqrt{3}}{4\sqrt{2}} \qquad h_3 = \frac{1-\sqrt{3}}{4\sqrt{2}}$$

Scaling coefficients for decomposition process are:

$$g_0 = h_3 \qquad g_1 = -h_2 \qquad g_2 = h_1 \qquad g_3 = -h_0$$

Dilation coefficients those used in reconstruction process are:

$$Ih_0 = h_2 \qquad Ih_1 = h_1 \qquad Ih_2 = h_0 \qquad Ih_3 = h_3$$

Scaling coefficients those used in reconstruction process are:

$$Ig_0 = h_3 \qquad Ig_1 = -h_0 \qquad Ig_2 = h_1 \qquad Ig_3 = -h_2$$

Figure 3 is an example of the sound level decrement data after wavelet thresholding process.

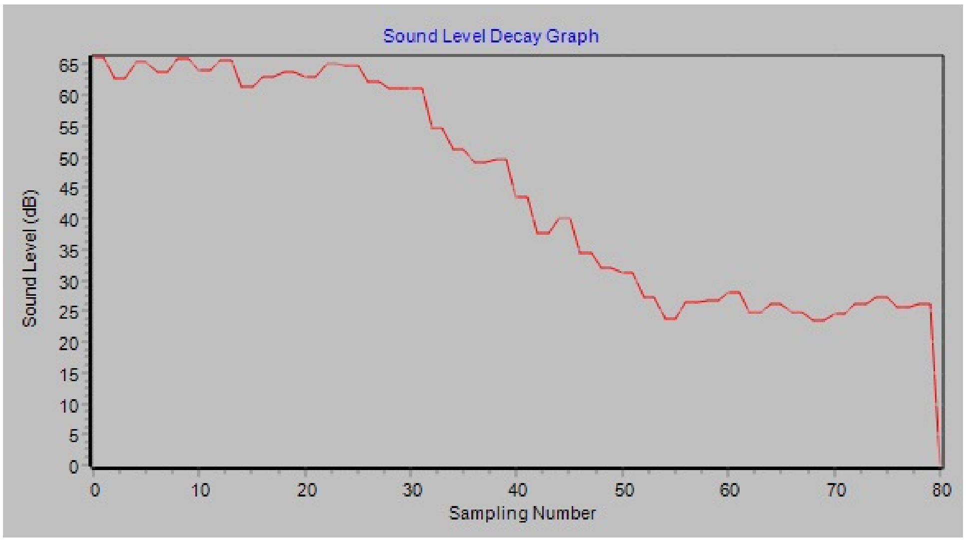

Figure 3. Plotted sound level data at frequency 160 Hz after wavelet thresholding process

From Figure 3 can be shown that the noise those occur in the data were removed makes the decrement slope of sound level is smooth and linear enough. Thus, the reverberation time can be computed easily. Another example is given in Figure 4 for unfiltered and Figure 5 filtered 350 Hz signal.

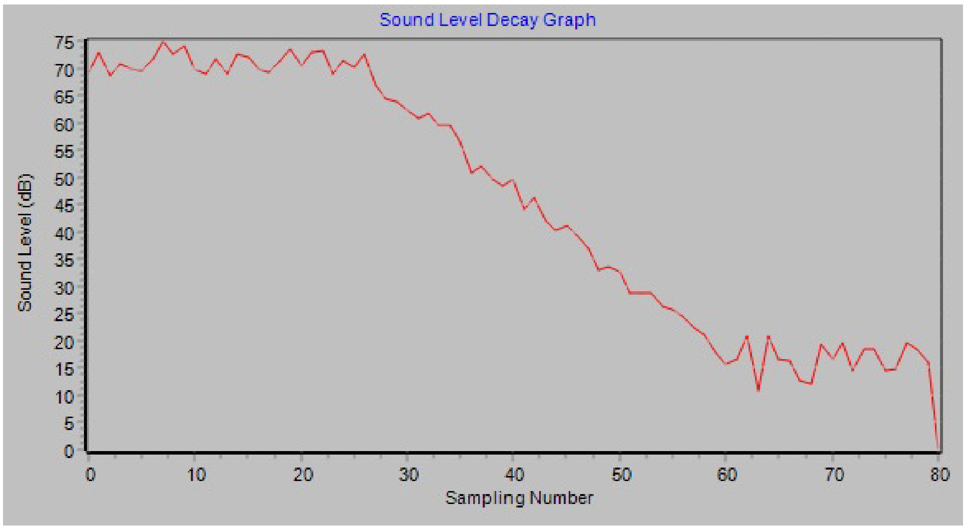

Figure 4. Plotted sound level data at frequency 350 Hz before wavelet thresholding process

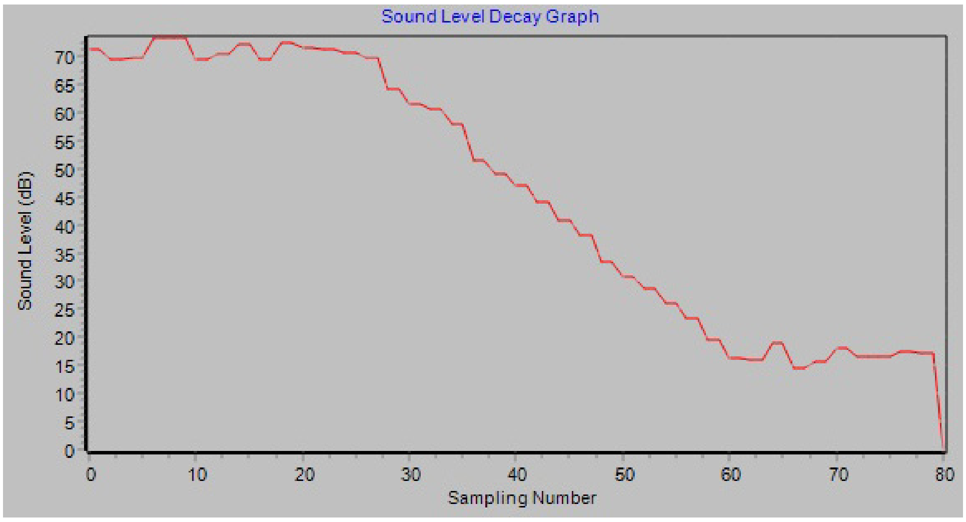

Figure 5. Plotted sound level data at frequency 350 Hz after wavelet thresholding process

From the figure 4 can be seen that there is a signal peak at sample number 27 whereas this point is the event when the sound source is switch off and the sound start to decay but due to some noise the sound is increasing for a moment before decay which can cause inaccurate reverberation time calculation. The same problem also occur when the sound level reach the background noise level, short time peak found in the signal. After filtering process this small peak can be smoothed and increasing the accuracy of reverberation time measurement.

Table 1 shows the result of reverberation time computation with and without wavelet thresholding.

From Table 1 can be seen that the average result of RT computation processing that passes wavelet thresholding is smaller than without wavelet thresholding. This is because the recorded sound level by real time analyzer is the total sound level between the real sound and the noise that occurs in the measurement process, makes the reverberation time is longer than it should be. During the filtering process, this noise is removed and more accurate estimation of reverberation time can be obtained.

Table 1. The RT result comparison without and with wavelet filter

Frequency	RT (seconds)	
(Hz)	No Filter	Wavelet Filter
125	2.4	2.0
160	2.6	2.6
200	3.0	2.6
250	2.8	3.0
315	3.8	3.4
400	3.6	3.6
500	3.8	3.8
630	4.0	3.8
800	4.2	4.0
1000	3.8	3.8
1250	3.6	3.4
1600	3.4	3.2
2000	3.4	2.8
2500	3.0	2.6
3150	2.6	2.4
4000	2.4	2.0

4. Conclusions

Wavelet thresholding method can be used to filter the noise in the measurement of reverberation time. Two level Daubechies is sufficient to filter the maximum and minimum peak which occur in the sound decay curve. The smooth decay curve is obtained after the filtering process therefore the reverberation time can be estimate easily from the curve.

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