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THE USEFULNESS OF WAVELET TRANSFORMATION TO REDUCE NOISE ON VIBRATIONS OF CABLE STRUCTURES

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Vibration testing applications have been used to examine a structure's dynamic behavior, such as determining the frequency values in cable structures. The accelerometer is used to record cable vibration data. Cable vibration data that has been mixed with noise has a non-periodic signal. In analyzing non-periodic signals using Fast Fourier Transforms analysis, there are obstacles in determining the reading of the frequency value. The study proposes a Discrete Wavelet Transform (DWT) to overcome the existing obstacles in analyzing the non-periodic signal. It can minimize the noise in the cable vibration data recording, making it easier to determine the frequency value of the cable structure, especially at the first vibration mode. In minimizing noises, the use of a scale factor of = 0.1 becomes the most effective value with the highest Signal Noise Ratio (SNR) value and the smallest Root Mean Square Error (RMSE). Other results obtained are Signal Noise Ratio (SNR) in the range of 2 – 5 dB, the type of noise in the cable structure is white noise and, the ratio of the standard deviation of noise (σ) to the amplitude (A) of recorded cable structure data with a range of 1 – 3.5.

Keywords: cable structure, noise, frequency, DWT

1 INTRODUCTION

In vibration testing, applications in the field have been used to check the dynamic behavior of pylon and bridge deck elements [3], determination of the frequency value of cable elements [10], and identification of cable damage [3, 11, 13]. Estimating the frequency from the vibration data of cable elements is very important and fundamental in theoretical and practical applications [12]. A simple sinusoidal wave's vibrational frequency can be easily determined by looking at the waveform in the time domain. Infield applications, noise, disturbances, and vibrations are often in the form of multi-tone sinusoidal signals with unknown frequencies [8].

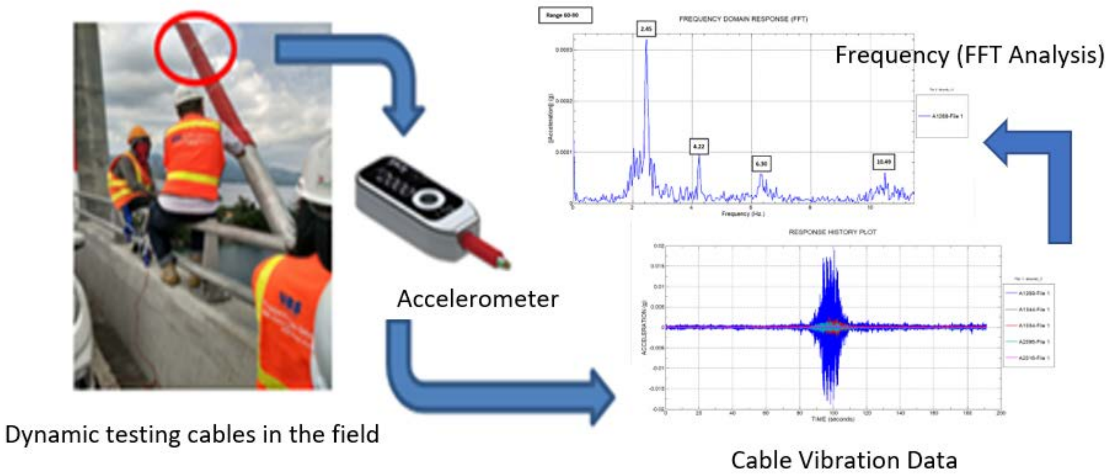

Fig. 1. Cable structure testing method for cable-stayed bridges (vibration-based)

In some cases of dynamic testing in the field as shown in Figure 1, the captured signal is in the form of a non-periodic signal (Figure 2). This becomes an obstacle in analyzing with Fast Fourier Transform. The obstacle that occurs is that the initial frequency has a fairly high amplitude. Amplitude peaks also appear in the initial frequency which causes doubts in reading frequency values, especially in determining the frequency of the first vibration mode (Figure 3). This obstacle was mainly caused by the cable vibration data, there will be noises of various levels, which are the noise at low, medium, and high frequencies [9]. For this reason, it is necessary to have a signal processing procedure that can detect and minimize the noise in the cable vibration data.

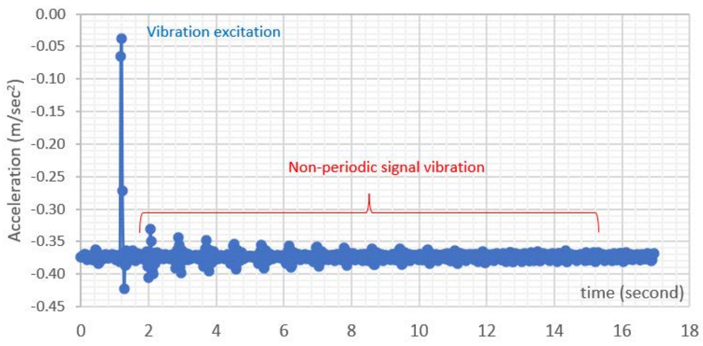

Fig. 2. Non-periodic cable element vibration data recording

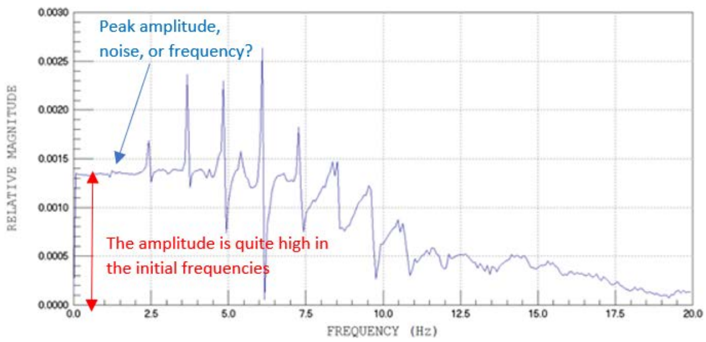

Fig. 3. Frequency analysis with Fast Fourier Transform for non-periodic signal

This research will add a Discrete Wavelet Transformation method to analyze cable vibration data. This Discrete Wavelet Transform has the advantage of performing signal processing, namely for non-periodic data signals [13], where this method is more detailed and simpler in conducting location data analysis and tracking high frequencies that occur with a short duration, as well as analyzing low frequencies in a long duration. In addition, Discrete Wavelet Transformation has another advantage, which is being able to minimize the noise in the signal data.

Wavelet transformation is a process or function that is used to represent the time and frequency information of a signal properly. The wavelet transform uses a flexible modulation window. This is what distinguishes it the most from the Short-Time Fourier Transform (STFT). STFT uses a fixed modulation window, this causes problems because a narrow window will give a poor frequency resolution and on the other hand a wide window will cause poor time resolution.

Figure 4 shows the comparison between STFT and Wavelet Transform. By using the wavelet transform, the signal can be decomposed into several levels, where each level will have a different window shape. At low decomposition level (green box), depicts low time resolution and high-frequency resolution. A higher level of decomposition (orange color box), illustrates high time resolution and low-frequency resolution.

By using the decomposition level on the Wavelet Transformation, it is possible to overcome obstacles that cannot be solved by STFT. Where the Wavelet Transformation can capture high-frequency signals well in time resolution and provide better information for low-frequency signals in frequency resolution.

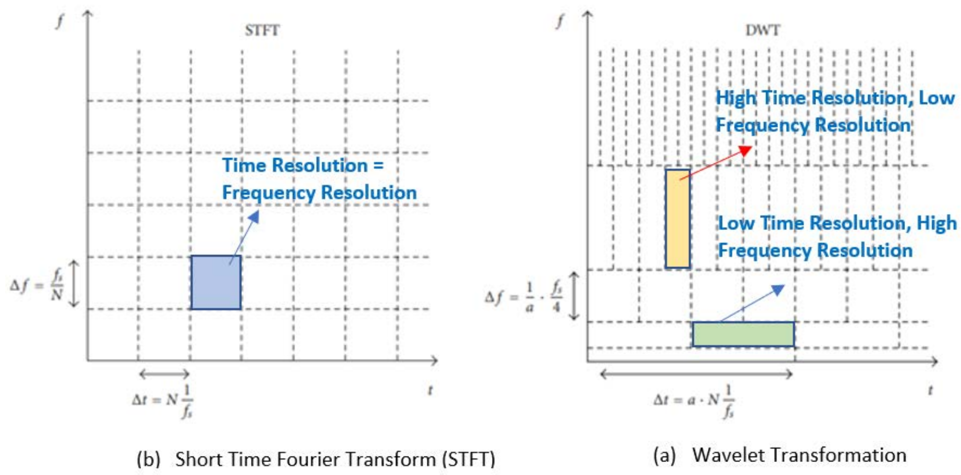

Fig. 4. Window comparison between STFT and Discrete Wavelet Transform [1]

2 MATERIALS AND METHODS

In this study, discrete wavelet transforms were developed to obtain frequency values from cable data recordings. Figure 5 generally shows a comparison of the analysis method developed in this study (method 2) and the previous analysis using the Fast Fourier Transform (method 1). Details of method 2 used in this study are presented in Figure 6.

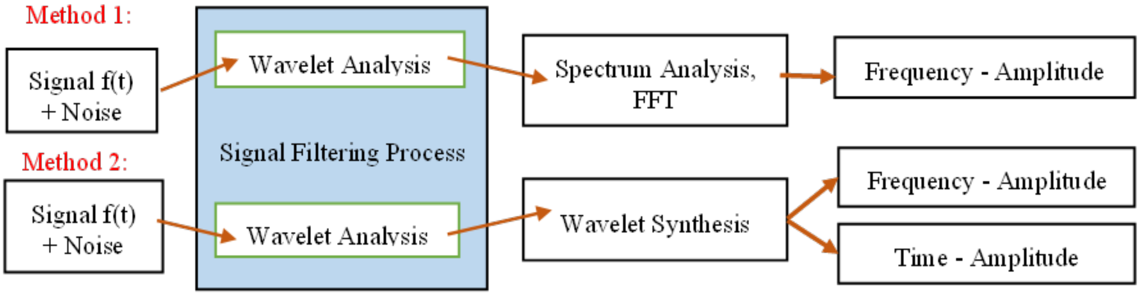

Fig. 5. The comparison of wavelet analysis signal filtering method using FFT spectrum analysis and wavelet synthesis

The calculation steps in analyzing the signal data from the vibration recording on the cable structure are as follows:

a. Open the cable vibration data file in notepad format. The cable vibration data captured by the accelerometer consists of reading the sample rate value (f_s) and the acceleration value starting from the initial data (x_1) to the final data (x_N), as shown in Figure 6.
b. Convert the row series of vibration data to excel format, x(n), and plot a graph of the function of time against acceleration.
c. Determine the Wavelet Decomposition (j) based on the number of data N = 512 to be analyzed. Calculation of the wavelet decomposition with the equation $N = 2^j$ so that j=9 is obtained. So that the value of j used in conducting the analysis is j = 0,1,2, ……., 8.
d. Identify the value of the standard deviation (σ) of the signal vibration data on the cable with the formula $\sigma = \sqrt{\sum(x_i - \mu)^2/N}$ where μ, x_i dan N are the average values of the original data, the vibration of the specific sample of data cable, and the amount of data analyzed.
e. Transform and filter the x(n) cable vibration data using Haar Wavelets highpass filter (H) = $\left\{{}^{1}/_{\sqrt{2}}, -{}^{1}/_{\sqrt{2}}\right\}$ and lowpass filter (G) = $\left\{{}^{1}/_{\sqrt{2}}, {}^{1}/_{\sqrt{2}}\right\}$ with filter length, m = 2 [2].
f. Calculate the Wavelet coefficient value $\omega_{j,k}$ with the formula (Wavelet coefficient = Haar Wavelet Matrix $H_{512x512}$ * x(n))
g. Determine the *threshold* (λ) value as a basis for noise reduction in cable vibration data. The threshold formula used is the universal threshold with the formula and improve based threshold with equation $\lambda = \frac{\sigma_n\sqrt{2lnN}}{log_2(j+1)}$ [7]. Where σ and N are the standard deviation of the noise and the amount of data vibration of the cable being analyzed.
h. Add the scale factor value (α) on the threshold function, so that the new equation of the threshold is $\lambda_1 = \alpha * \lambda$. The scale factor used in this study is in the range of 0.1 to 1.0.
i. Enter the threshold value (λ_1) into the Wavelet Threshold Function. The Wavelet Threshold function used is Hard Threshold [4], Soft Threshold [13], Garrote Threshold, and Improved Threshold [7].
j. Perform the noise reduction process with the criteria for the absolute value of the Wavelet coefficient below the threshold number will change to zero ($|\omega_{j,k}| < \lambda_1 \rightarrow \overline{\omega_{j,k}} = 0$).
k. Calculate the noise-reduced cable vibration data with the equation ($(x(n))_{noise}$ reduction = Haar Wavelet Inverse Matrix $H_{512x512}$ * Wavelet Coefficient Reduced)
l. Determine the most effective Wavelet Threshold function in reducing noise. The effective criteria are having the largest Signal Noise Ratio (SNR) value in decibels (dB) and the smallest standard deviation value. SNR formula with equation SNR = log10 (μ^2/σ^2). Variables μ dan σ is the average value of the original data and the standard deviation of the noise, respectively.
m. Recommend scale factor value (α) at the most effective threshold for noise reduction.
n. Obtain the pattern of the original vibration of the cable structure
o. Obtain the type of noise that occurs in the cable structure
p. Determine the cable structure's frequency value, which is clearer after the noise reduction process is carried out.

In the form of a flow chart, the calculation steps for noise reduction from the vibration data recording x(n) are shown in Figure 7.

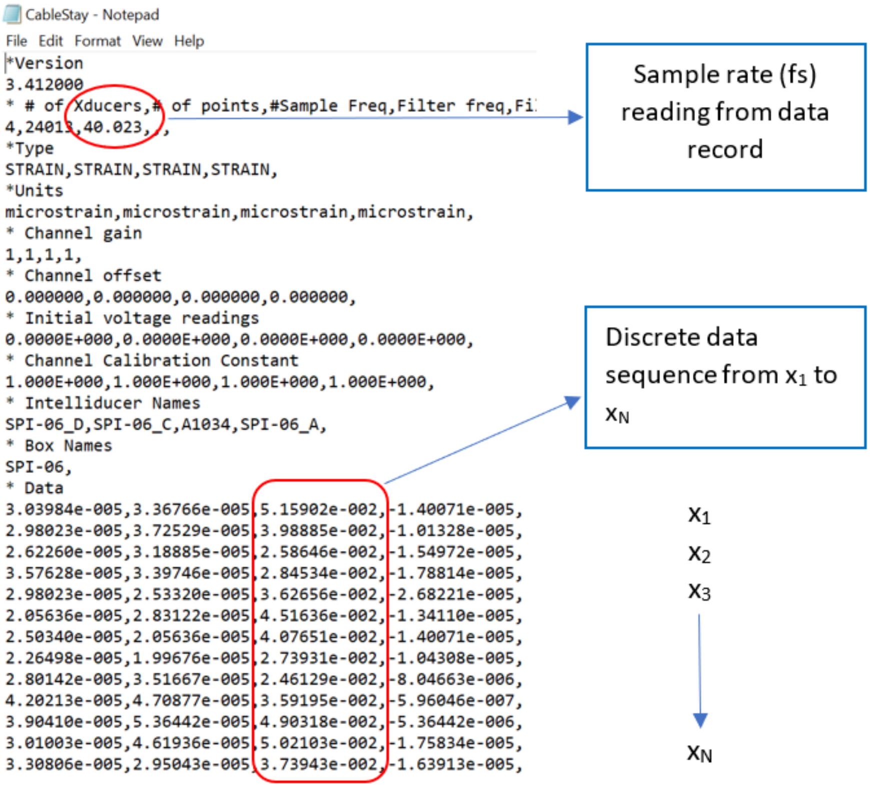

Fig. 6. Data recording from the accelerometer in the notepad program

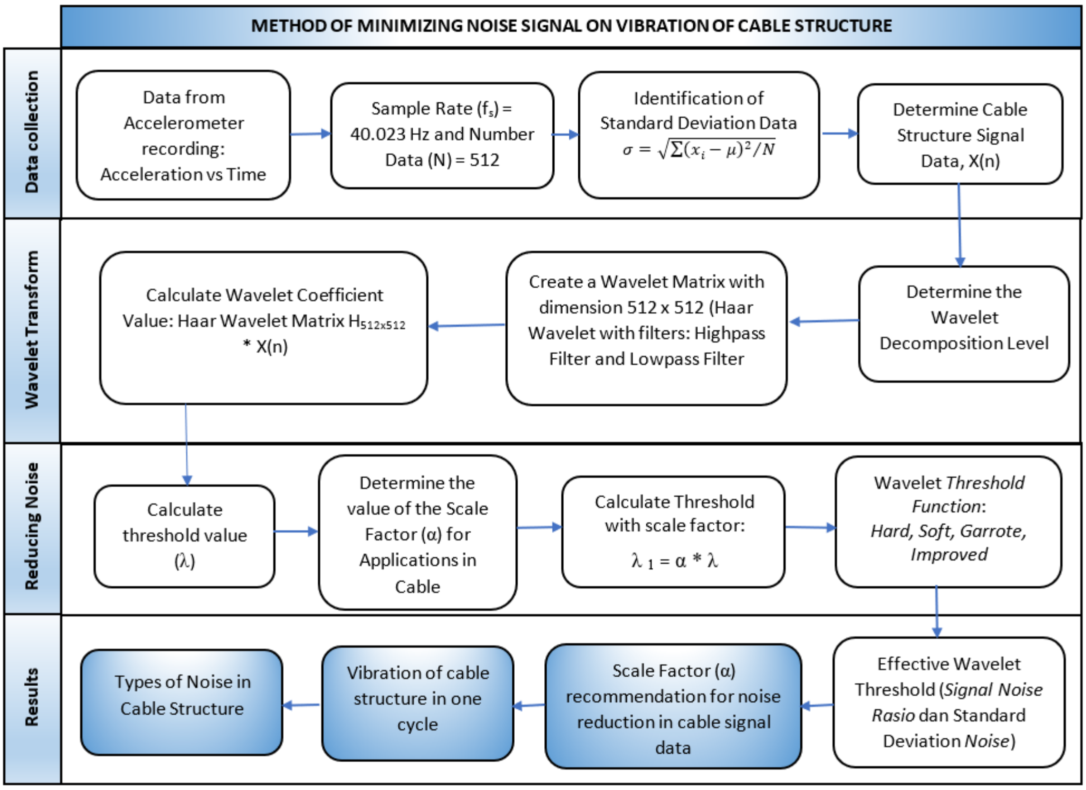

Fig. 7. Method of minimizing noise in cable structure

In doing the transformation from discrete data x(n) into wavelet coefficients by passing discrete data x(n) using Discrete Wavelet Transform. Use of Discrete Wavelet Transform based on scale (j) and shift (k) values. The scale value (j) is determined using the level of decomposition. The level of decomposition is influenced by the number of data N, so the analysis will start from j = 0 to j = 8 (calculation see step no.3). Discrete Wavelet Transformation Formula ($\omega_{j,k}$) uses the equation as in equation 2.

Wavelets have several derivatives called baby wavelets, where the use of baby wavelets is adjusted to the needs of the analysis. The baby wavelet used in this study is the Haar wavelet with the equation

$$\psi(t) = \begin{cases} 1 & 0 \le t \le 1/2 \\ -1 & 1/2 < t < 1 \end{cases} \qquad (1)$$

In the form of a mathematical equation Haar Wavelet has the following equation:

$$\omega_{j,k}(t) = \sqrt{2^j}\,\omega\left(2^j\,t - k\right) \qquad (2)$$

So that the mathematical equation of the Wavelet Transform using the Haar Wavelet and the highpass filter function is as follows

$$\omega_{j,k}(n) = \frac{1}{\sqrt{2^j}}\sqrt{2^j}\,\frac{1}{\sqrt{2}}\,\psi\left(2^j\,t - k\right) \qquad (3)$$

The results of discrete data transformation x(n) using discrete wavelet transform produce wavelet coefficient values as shown in Figure 8.

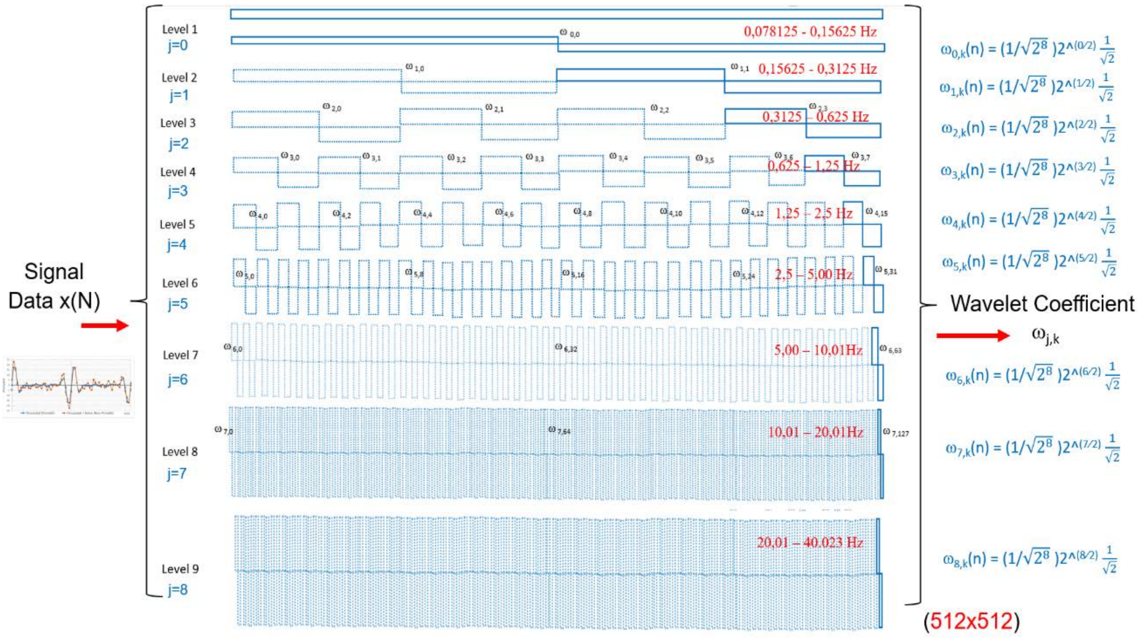

Fig. 8. Wavelet coefficient calculation schematic

3 RESULTS AND DISCUSSION

Based on the calculation results obtained several results as follows:

3.1 Identify the standard deviation value of the signal data recording

Data recording from the accelerometer on the cable as a function of time is proportional to the acceleration as shown in Figure 9. In the time function, the recorded data results are read in a time duration of 16.94 seconds or if converted into series data it becomes 679 data points.

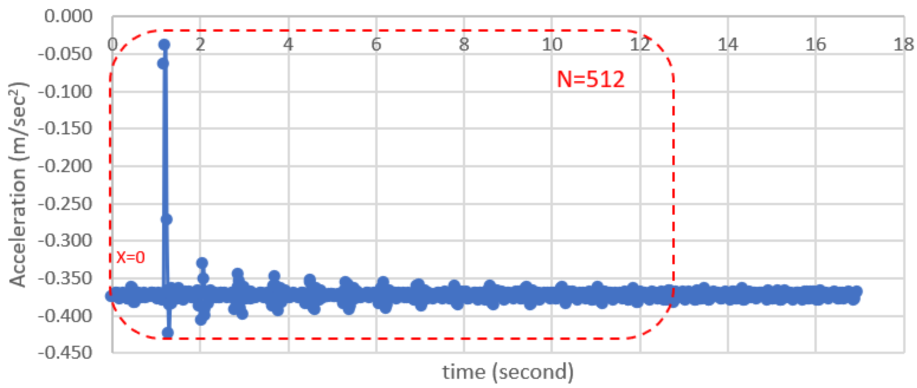

Fig. 9. Cable data recording in time function

Identify the value of the standard deviation of the signal data using the amount of data N = 512. The calculation of the value of the standard deviation of the data starts from x=0 to x=511 with a standard deviation value of 0.0218. The calculation of the standard deviation value is continued by shifting the initial data value, namely x=48 to x=559 with a value of 0.0170. The calculation step is continued with the last step, namely x=160 to x=671 with a value of 0.0052. The results of the standard deviation values of the signal data are shown in Figure 10.

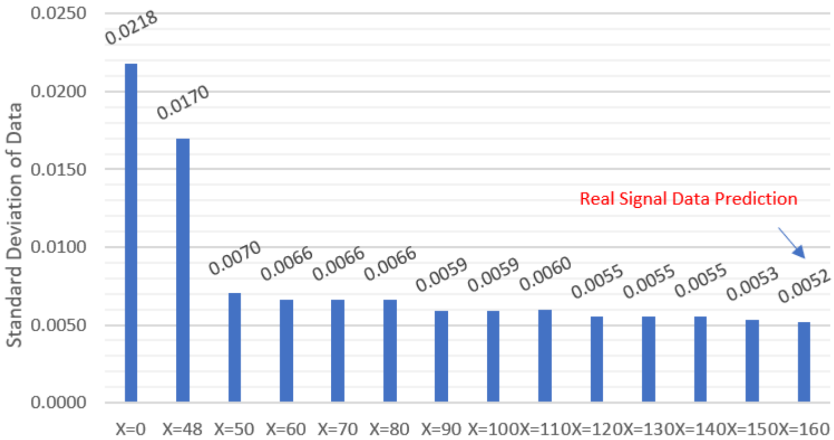

Fig. 10. The value of the standard deviation of the data cable multiple analyzers X_{start} to X_{end} (N=512)

Based on Figure 10, the standard deviation value when the starting point of the analysis X = 0 is 0.0218. At the starting point of the analysis X = 48, the standard deviation value begins to decrease to 0.0170. Point X = 48 is the point of data generated when the cable is hit with a hammer. It can be seen in Figure 9, that his generation point represents the maximum deviation value of the data in the time domain. After passing the generation point data, the standard deviation value of the data decreased significantly, 0.007 at the time of the analysis of the starting point X = 50. And when the analysis of the starting point continued to shift to the right with the starting point X = 60 to X = 160 the standard deviation value data continues to decline.

The value of the decrease in the standard deviation of the data is greatest when the starting point of the analysis is X = 160, which is 0.0052. Based on Figure 10, it can be used as material for predicting the original signal data on the cable, namely at the starting point of the X = 160 analysis, and used as material for further analysis to minimize the noise in the cable data recording.

3.2 *Cable structure frequency value*

After obtaining the frequency value of the cable structure through signal processing which is analyzed from x = 160 to x = 671, the next step is to reduce noise in the data recording from x = 0 to x = 511. The noise in the data recording x = 0 up to x = 511, is the result of the difference between $x_0(t)$ data and $x_{160}(t)$ data. The form of an equation is shown as follows.

$$N_{x=0}(t) = x_0(t) - x_{160}(t) \quad (4)$$

The results of the frequency domain graph comparison for recorded cable data analyzed from x = 0 to x = 511 with data reduced by noise and without noise reduction as shown in Figure 11. With the noise reduction process, the lowest structure frequency value is up to the highest frequency that can be read clearly. This can be seen from the dominant amplitude values at the frequency points of the cable structure. Apart from the frequency value of the cable structure, the amplitude value in the range of 0 – 20 Hz has an amplitude value that is close to zero (0).

Based on the identification in Figure 2, for cables with initial data x = 0 and final data x = 511 which were analyzed using the Fast Fourier Transform, there are still doubts about identifying the frequency value at the beginning. In the frequency range of 0 – 2.5 Hz, especially at the point around the 1.25 Hz value, there is a subtle amplitude value. By analyzing the discrete wavelet transform and minimizing noise with the wavelet threshold function, it is found that the amplitude can be minimized. So, the conclusion is that the frequency value of 1.25 Hz is not the first frequency of the cable.

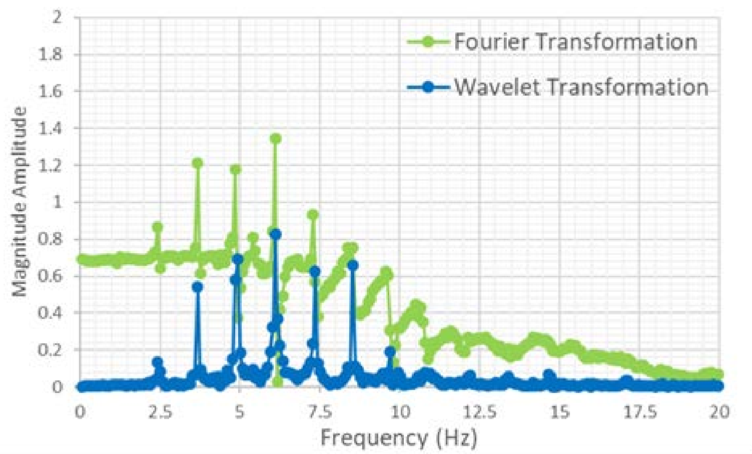

Fig. 11. Comparison of frequency values with and without noise reduction for x=0 analysis on cables

3.3 *Threshold scale factor (α) value*

The recommended scale factor value (α) for the basis threshold (λ) for cable structural elements is 0.1 as shown in Figure 12. The scale factor value of 0.1 is the value with the highest Signal Noise Ratio value and the smallest noise standard deviation. The results of the comparison of research using the scale factor on cable elements with previous studies for the health sector and gamma spectrum signals are shown in Table 1.

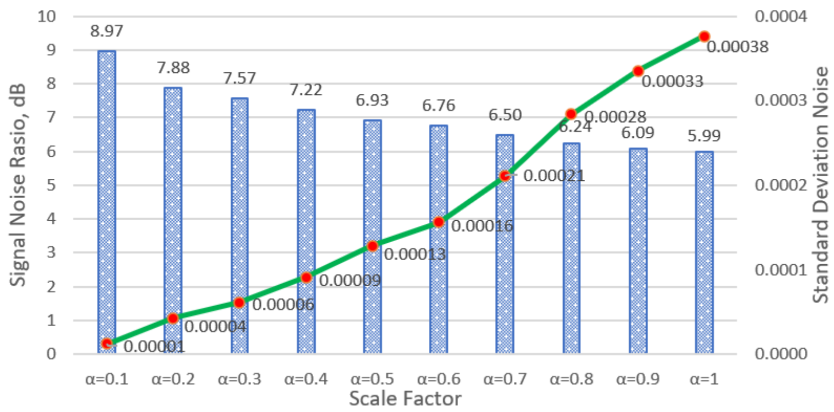

Fig. 12. Comparison of SNR Value and Noise Standard Deviation Using Hard Threshold Function

Table 1. Proposed scale factor (α) for cable structure

No	Signal Data	Transformation Analysis	Threshold ($\lambda_1 = \alpha.\lambda$)	Scale Factor (α)
1	Noise reduction signal phonocardiography (PCG) in the diagnosis of cardiovascular disease [6]	Wavelet Transformation	√	1.3 – 1.4
2	Noise reduction in gamma spectrum signal processing is caused by radioactive statistical fluctuations [15]	Wavelet Transformation	√	0.7 – 1.0
3	Noise Reduction in vibration signal processing in Cable-Stayed Bridge Cables	Wavelet Transformation	√	0.1

3.4 *Type of noise on cable*

After getting the vibration signal on the cable in Figure 13, the next step can be to take into account the noise pattern. The noise pattern on the cable can be seen from the comparison of the Signal Noise Ratio and frequency values. To calculate the value of the Signal Noise Ratio using a comparison of the original signal data of the cable structure with the noise that occurs in the cable.

The original signal data of the cable structure is the result of the calculation of the signal data which has been reduced by noise. While the noise data is the difference between the cable signal data x=0 and the structure signal data that has been reduced by noise (Nx=0(t) = x0(t) – noise reduction(t)). The results in Figure 13 show that the noise at low and high frequencies has approximately the same value. So the conclusion that can be drawn from the noise pattern on the cable is White Noise.

The Signal Noise ratio value range for cables is in the range of 2 dB – 5 dB. The positive number of the Signal Noise Ratio value illustrates that the original signal amplitude value is greater than the noise amplitude acting on the cable vibration signal data.

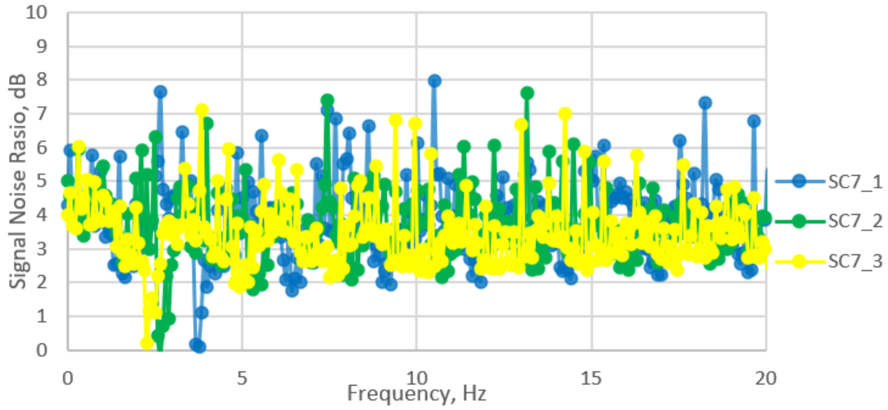

Fig. 13. Noise pattern on cable

3.5 *Calculation of the ratio of noise and amplitude on the cable*

The value of the vibration amplitude on the cable is obtained from the vibration reading of the cable structure data that has been reduced by noise. Figure 14 is the original vibration pattern of the cable and then analyzed the amplitude value that occurs in the cable. The signal amplitude value for each cable is selected from the largest amplitude value to the smallest amplitude value. The calculation of the amplitude value and the noise ratio compared to the cable signal amplitude can be seen in Table 2.

Table 2. Calculation of noise ratio and cable amplitude

No	Coordinate Point (m/sec^2)	Vibration Median (m/sec^2)	Amplitude (A)	Noise (σ)	Ratio (σ/A)
1	-0.353	-0.3725	0.0195	0.0203	1.04
2	-0.3556	-0.3725	0.0169	0.0203	1.20
3	-0.3562	-0.3725	0.0163	0.0203	1.25
4	-0.3586	-0.3725	0.0139	0.0203	1.46
5	-0.3596	-0.3725	0.0129	0.0203	1.57
6	-0.3611	-0.3725	0.0114	0.0203	1.78
7	-0.3615	-0.3725	0.0110	0.0203	1.85
8	-0.3628	-0.3725	0.0097	0.0203	2.09
9	-0.3632	-0.3725	0.0093	0.0203	2.18

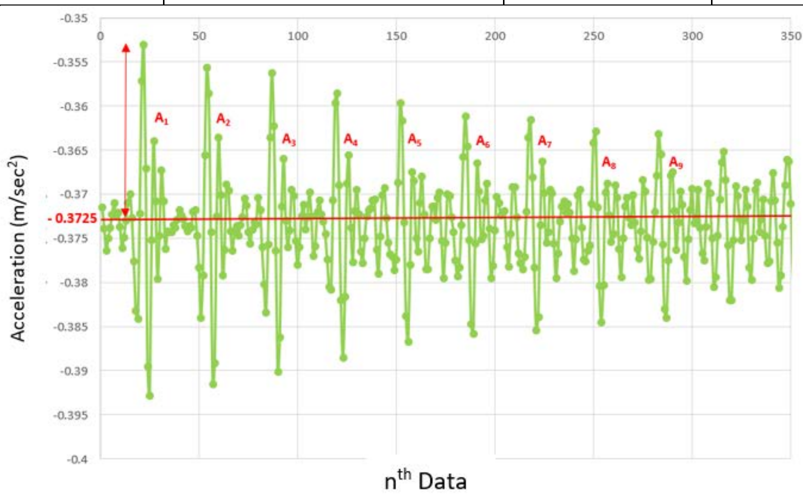

Fig. 14. Cable amplitude value

After obtaining the results that the ratio of noise ratio and signal amplitude to the vibration of the cable structure is 1.65 – 2.18. With these results, for cables when analyzed using the Fast Fourier Transform, there are doubts in reading the structure frequency values, especially at the beginning of the frequency. So it requires another analysis, namely Discrete Wavelet Transformation to clarify the reading of the frequency value of the cable structure.

Meanwhile, the results of the parameter study using a sinusoidal signal by comparing the noise value to the signal amplitude get an idea that the structure frequency can still be read clearly in the case of the noise ratio and signal amplitude being less than one. For the case of the noise to signal amplitude ratio of more than 3.5, the structure frequency reading is no longer legible. Meanwhile, in the case of the noise ratio and signal amplitude of 1 – 3.5, the frequency can still be read but has begun to be disturbed in reading the frequency value (Figure 15). This is due to the emergence of other amplitudes that are not the structure frequency amplitude.

From the results of the comparison of noise and signal amplitude on the vibration of the cable structure with a range of 1.65 – 2.18, the reading of the frequency value has been disturbed. And from the results of the parameter study using a sinusoidal signal for the noise ratio and signal amplitude with a value of 1 – 3.5 the reading of the structure frequency has also experienced interference. So additional analysis is needed, namely using Discrete Wavelet Transform, threshold basis with scale, and Wavelet threshold function in carrying out the noise reduction process in the signal.

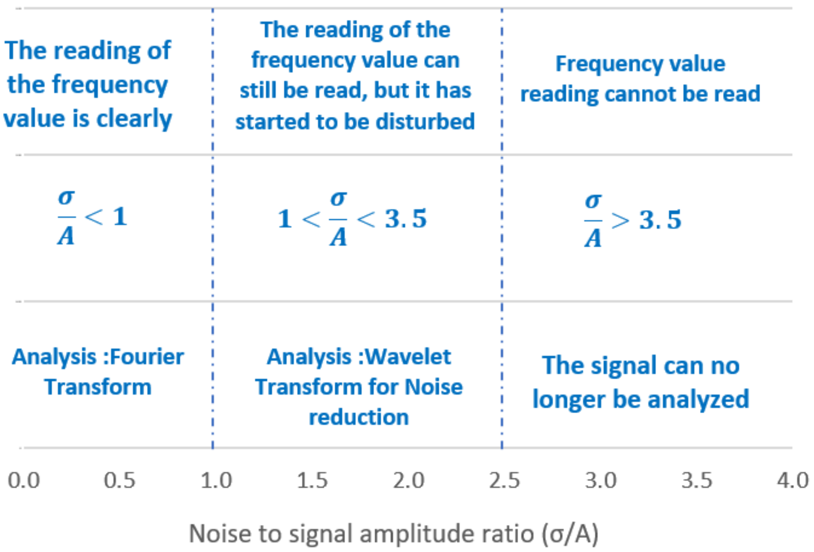

Fig. 15. Summary of research results of frequency value analysis based on noise ratio and signal amplitude

4 CONCLUSIONS

The conclusions that can be drawn in this study are as follows:

- The value of the noise ratio and the signal amplitude of the cable has a value of 1.65 – 2.18. So, it is necessary to reduce noise using Discrete Wavelet Transform analysis, using a scaled threshold basis, and threshold function to reduce noise. So that after noise reduction the frequency reading of the cable structure can be read more clearly.
- The use of the threshold value is effective in minimizing noise, with a recommended scale factor value of = 0.1.
- Identification of the noise that occurs in the cable, namely white noise. The noise that works on the cable for low frequencies to high frequencies has a Signal Noise Ratio value that is approximately the same with a range of values ranging from 2 to 5 dB.

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