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Article

Design of an Acoustic-Based Nondestructive Test (NDT) Instrument to Predict the Modulus of Elasticity of Wood

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Abstract. Modulus of elasticity (E) can predict the mechanical characteristics, as well as grade the quality of wood. The Destructive Test (DT) method is the more commonly used, where the wood sample is split up when being tested. This research used the NDT method based on the longitudinal stress wave method (LSWM) whilst utilizing handheld instruments. The calculated E-dynamic (E_d) from the NDT method was compared with the E-static (E_s) from the DT method to validate the technique. Six different wood types were tested with ten samples of each kind. An average R-value of 0.898 was obtained, indicating a high correlation between the E_d values and E_s values. The LSWM method requires reliable hardware and software to record the impulse response. It starts by hitting the wood with a hammer to create an impulse, finding the resonance frequency (f_0), and later calculating the E_d. A more practical and easy-to-use handheld mobile instrument was developed using a Raspberry Pi-2 microcomputer as the signal processor, an LCD touchscreen, a USB soundcard, and a dynamic microphone that covers 0.1-5kHz and -64 ± 3dB. An internal telecommunication system is provided to support measurements conducted at lumber mills. The software includes band-pass filtering of the recorded spectrum where the f_0 is depicted. A time-domain envelope fitting is then applied to the filtered spectrum to obtain the $R^2_{envelope}$. A low $R^2_{envelope}$ value indicates an inadequate impulse response, and therefore, the test should be redone.

Keywords: Nondestructive test, longitudinal stress wave, instrumentation, wood, modulus of elasticity.

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1. Introduction

Indonesia is one of the top wood exporters in the world, being a country with a forest cover of 46.33% or 88.17 million ha of the forest [1]. According to the data from World's Richest Countries in 2015, Indonesia exported 3.2% of the world's wood exports, an equivalent of $4 billion, and also ranked seventh among the top wood exporters [2]. This number has increased by 0.3% compared to the amount in 2014 [3]. Therefore, wood is an essential commodity in Indonesia. The wood's quality is classified by using a grading system, one of which relies on the modulus of elasticity (E) value to predict the mechanical characteristics of the wood. Knowing this characteristic is critical when it is used as a construction material. A typical wood grading technique is using a qualitative method by visual inspections. This method is not accurate since the wood of a tree used for lumber can vary, and the properties of every tree are not homogeneous.

The quantitative method provides more accurate grading. It involves a few rigorous procedures that are sometimes complex and causes the assessment to be slower in some cases. The Indonesia National Standard number 7973-2013 that was published regulates a grading system standard for assessing the wood quality [4]. The elasticity constant is a vital mechanical property parameter of wood and reflects the resistance to deformation under external forces [5].

There are two methods for measuring E, i.e., destructive evaluation and nondestructive evaluation. The destructive evaluation involves some samples to be destroyed as a representation of the whole population member using a grading machine [6]. It also uses some complex measuring instruments, which lead to a slow evaluation process. The most significant disadvantage of the destructive method is that the remaining wood sample can no longer be used since it has been intentionally broken apart during the test. The modulus of elasticity measured will be labeled as E-static (E_s).

Nondestructive test (NDT) to predict E-dynamic (E_d) has been developed. For wood, there are some nondestructive evaluation methods, i.e., static bending, transverse vibration, and longitudinal stress wave [6]. This research proposed an NDT method based on the Longitudinal Stress Wave Method (LSWM). It developed a more practical and easy-to-use handheld instrument that enables the grading process to be done at the location where the wood is being sold or at the lumber mill (not necessarily in a laboratory).

The LSWM method requires reliable hardware and software to record an impulse response created by hitting the wood with a hammer, followed by finding the resonance frequency (f_0), and then calculating the E_d. The results of the E_s and E_d are then compared to ensure the LSWM test is a reliable method. Furthermore, a technique to check the quality of the impulse response was introduced in the software. This step is required since there is a possibility that the recorded signal obtained from the LSWM contains a large portion of noises.

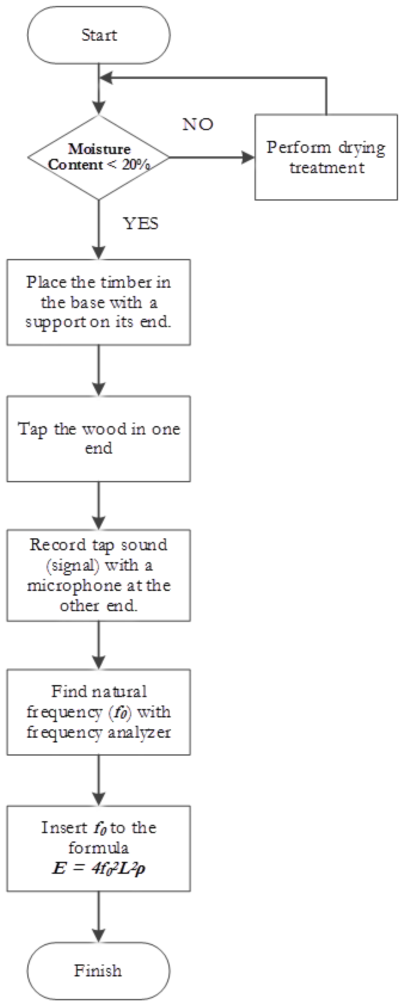

Fig. 1. The preliminary study of LSWM for predicting the E_d of wood.

Noises are due to the presence of background noise, a poor impulse sound produced by the tapper (hammer), and the sound from the friction between the wood and the supporting system.

2. Method to Validate the Use of LSWM in Predicting E_d

The LSWM for predicting the E_d of wood is based on acoustic measurements with the steps shown in Fig. 1. Tested timbers are placed on a simple supporting structure, and an impulse is produced by giving an impact at one of the end using a hammer. The tap method using an impulse sound was feasible not only for small beams but also for commercial size construction lumber in obtaining their Young's moduli [7].

A longitudinal sound wave will propagate through the wood, and the impulse response is recorded at the other end. The recording tools are a BSWA type MPA-201 microphone supported by a BSWA-Tech signal conditioner and connected to a notebook. The signal processing software was Cool Edit Pro 2.0, Yoshi masa Real-Time Analyzer, and Matlab.

Table 1. Description of the wood tested.

Types of Wood	Dimension (cm)	Density (kg/m^3)
Sukun	120 x 12 x 6	400
Munggur	120 x 12 x 6	500
Mahogany	120 x 12 x 6	700
Teak	120 x 12 x 6	750
Sonokeling	120 x 12 x 6	800
Acacia	120 x 12 x 6	900

Another set of devices for this preliminary research to prove the reliability of the LSWM test consisted of a microphone plugged into a 3.5-inch resistive touchscreen display and the N-tier application architecture for implementing software as the interface to read the resonant frequency observed. In digital signal processing, it is vital to spend more time examining issues of sampling [8]. The sampling theorem stated that a bandlimited signal could be precisely reconstructed if it is sampled at a rate at least twice the maximum frequency component in it. The sampling frequency and overall observation interval are equal to 1kHz and 3s, respectively [9].

The measurement starts by checking the moisture content of the wood, which was expected to be less than 20%. There are 60 samples of wood in total, with the types (common name in Indonesia), dimensions, and densities provided in Table 1. Sonokeling (D. latifolia) and Mahogany (S. mahogany) had the best acoustical properties, ultrasonic wave velocity, and ratio of wood stiffness to wood density among the others [10].

The E calculation (both for E_s and E_d) does not depend on the existence of a wood knot. The quantitative evaluation of knots will be accomplished by measuring Δf, where Δf shows the difference of resonance frequency between the sample that contains a knot and the clear sample [11]. The frequency spectrum of the recorded impulse response, of the tapped wood using the settings above, was analyzed. The spectrum contains both fundamental and resonance frequencies. The fundamental frequency (the lowest frequency with the highest magnitude) value is then used to obtain the E_d value, according to the formula [12]:

$$E_d = 4 f_0^2 L^2 \rho \tag{1}$$

where f_0 is the fundamental resonant frequency, L is the length, and ρ is the density of the wood. The wood with higher density and stiffness passes longitudinal stress waves with greater velocity [13]. One of the spectra from the longitudinal stress wave signals recorded of Mahogany woods is shown in Fig. 2 [14] [15]. Using the signal processing tools, the estimated f_0 was calculated an is shown as 1.48kHz with a magnitude of -76.58 dB).

After the E_d values of all samples were measured, the samples were brought to the Structure Laboratory at the Department of Civil Engineering to be tested for the E values using the Destructive Method. Tools and procedures of the modulus of elasticity static (E_s) values followed the ASTM D143-94 [16].

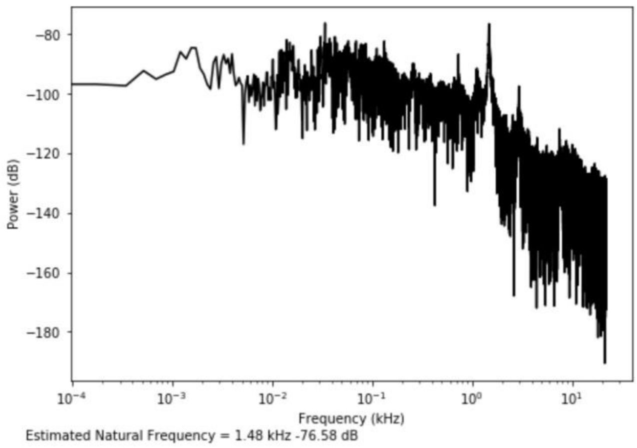

Fig. 2. The mahogany #1 sample obtained from a previous study [15].

Table 2. The coefficient of determination R^2 for the relationship between E_d and E_s.

Wood Type	Scientific Name	R^2	Freq. Range of f_0 (Hz)
Sonokeling	*Dalbergia latifolia Roxb.*	0.57	-
Teak	*Tectona grandis L.f.*	0.59	1300 – 1738
Sukun	*Artocarpus altilis*	0.63	1313 – 1477
Acacia	*Acacia mangium*	0.90	1201 – 1616
Munggur	*Pithecolobium Saman Benth*	0.90	1164 – 1760
Mahogany	*Swietenia spp.*	0.95	1042 – 1913

The procedure was continued by conducting the NDT for all 60 samples using the steps shown in Fig. 1, the wood went through the DT to obtain the E_s values. The values of E_d and E_s were compared for each wood type, and R^2 values were obtained to predict the correlation of each wood type, as shown in Table 2. The frequency range of f_0 of the 60 samples studied is also provided. The minimum and the maximum frequencies are 1041.90Hz and 1913.30Hz. The Mahogany wood is the wood with the highest R^2.

Figure 3 describes the comparison of the five wood types but excluded the Sonokeling wood since the correlation for this specific wood type was already weak. The R^2 for all six wood types in Table 2 are unrelated with their density shown by the Munggur wood with the second-lowest density but having the second-highest R2 value between Ed and Es. The moisture condition varied and intentionally neglected for all wood types. Hence, the experiment results might be related to both moisture and density. It is a consideration that shall be taken into account in the future when conducting similar experiments.

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3. Development of the Handheld Instruments

The main idea of this research is to create an audio spectrum analyzer. We defined the frequency response specifications for the instrument as 800 – 4100Hz using the results from the preliminary LWSM, with the resonant frequency of the steel, the minimum, and the maximum frequency being 3953.90Hz and 3970.80Hz, taken into account [14]. As a buffer, the lower limit was decreased, and the upper limit was increased. The instrument is expected to be robust, easy to use, and mobile. The device is designed to be a semi-automatic instrument that records the longitudinal stress wave and processes the data signal to yield the E_d.

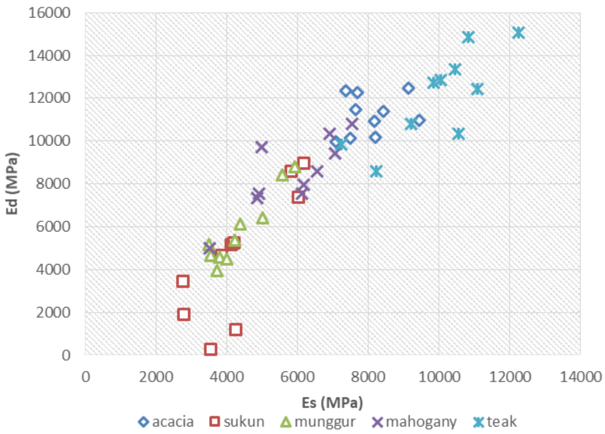


Fig. 3. Comparison between the E_d and E_s values of 5 wood types (50 samples) with an R^2 of 0.827.

3.1. Main Design

In a laboratory test, measurement of the longitudinal f_0 of wood is conducted by using a personal computer, either a desktop or laptop. They use a built-in FFT [17] module embedded in the software, i.e., MATLAB, Scilab, etc. For maintaining the robustness and the mobility of the instrument, the instrument was designed to be able to calculate the NDT results directly on the instrument's display. A complete hardware structural design of the device is shown in Fig. 4(a).

The sensor system consists of a dynamic microphone that has a frequency range of 100–5000Hz and a USB soundcard as the Analog-to-digital converter to sample the signal. The processing unit used a single board computer called Raspberry Pi-2 (Rpi) with Raspbian Linux as its operating system. It was embedded with quad-core Broadcom BCM2835 900MHz CPU, equipped with 4-USB ports, and some integrated communications ports, i.e., SPI, I2C, and UART. One of the most interesting facts is that it only consumed around 5W of power.

For the user interface, a 3.5-inch resistive touchscreen display was used to exclude the need for a keypad. The complete diagram of the N-tier application architecture for implementing the software for digital signal processing and user interface on the Raspberry Pi is shown in Fig. 4(b). The recorded audio files are stored in the data layer using a Linux file system. For the business or logic layer, it used a Python programming language with Scipy and Numpy library embedded. For the presentation layer, a graphical user interfaces library Tkinter and graph plotting library Matplotlib is used. The instrument was designed to be semi-automatic with an operating scenario, as shown in Fig. 5.

The user should input the parameters regarding the wood sample, including wood code, weight, length, cross-section length, cross-section width, and record duration. After the parameters appropriately inputted, the user can record the stress wave signal. The signal in time-domain automatically appears when recording stops.

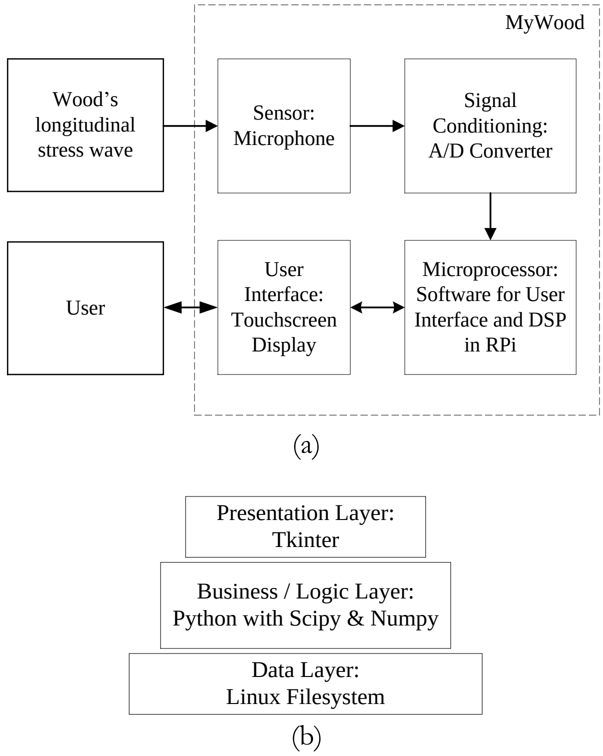


Fig. 4. The proposed instrumentation system design of 'MyWood': (a). diagram of components; (b). The N-tier application architecture for software implementation.

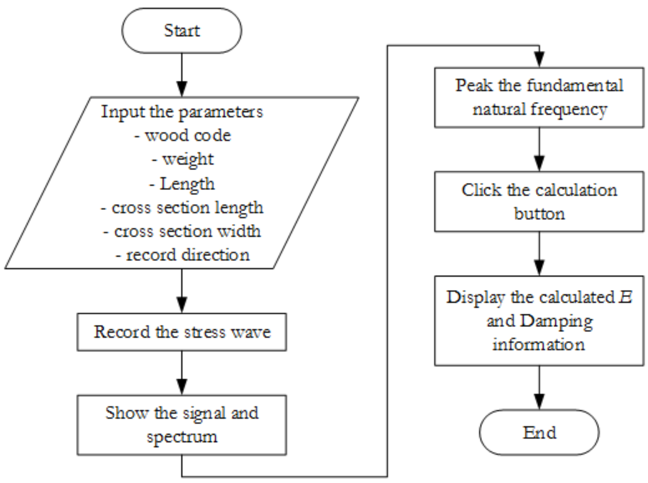


Fig. 5. The main design of the measurement procedure of 'MyWood' instrument.

After the recording process, a signal in the frequency domain can be seen on the interface. Users can then pick the fundamental frequency and use it to calculate E using Eq. (1). The fundamental resonant frequency is the resonant frequency, which has the highest magnitude, but the lowest frequency. All information is shown on a touch screen display with four main parts of the main view, i.e., the plot area, plot toolbar, side tool, and pointer position status, as shown in Fig. 6.

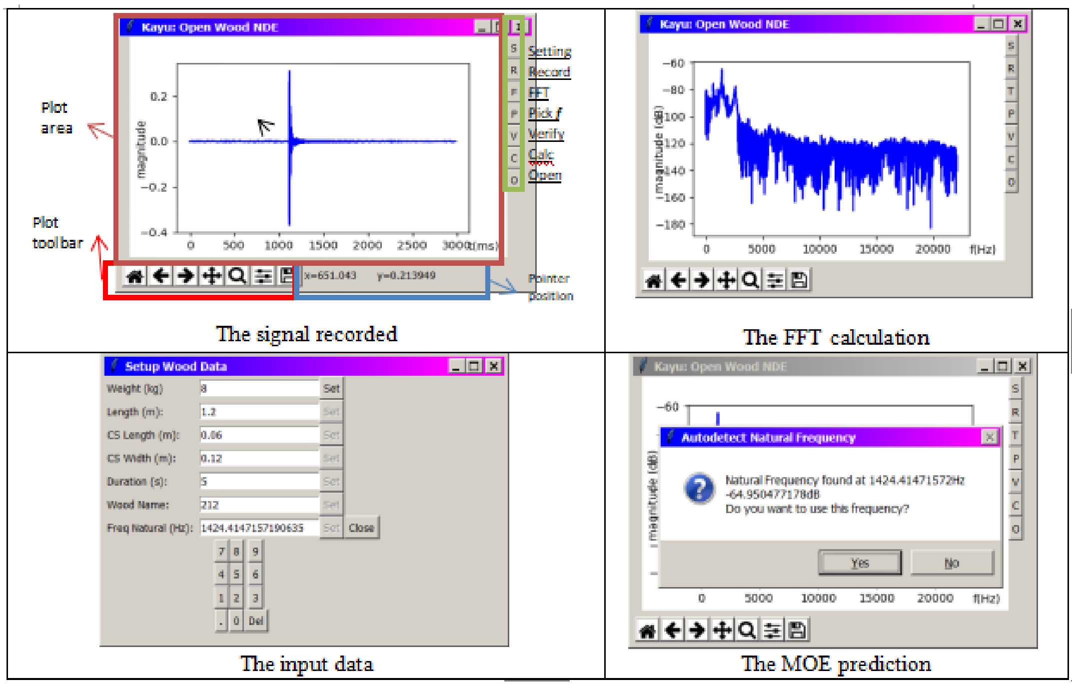


Fig. 6. The user interface of the instruments to predict E of wood (E_s).

3.2. Microphone and Soundcard Performance Test

The performances of both microphone and soundcard were evaluated by testing the frequency response, sensitivity of the receiver, and waveform. This sensor system was able to work in the desired frequency range, which is 800Hz to 4100Hz. However, the frequency response declined in the 800Hz to 2700Hz range with a sensitivity difference of ± 15 dB, which is quite poor. However, since the aim is to identify the first frequency of the peak response of an impulse, this sensitivity discrepancies effect to the results can be ignored.

The waveforms that were tested are a square wave, sine wave, and triangle wave. Input signals are created from an oscilloscope, and the instrument provides readings of the signals. Similar results are shown on both readings of slight distortion for the square wave, as shown in Fig. 7(a) and (b). No adjustment is needed for the soundcard since it performed well in the desired frequency range and has an average magnitude of -11.86 dB.

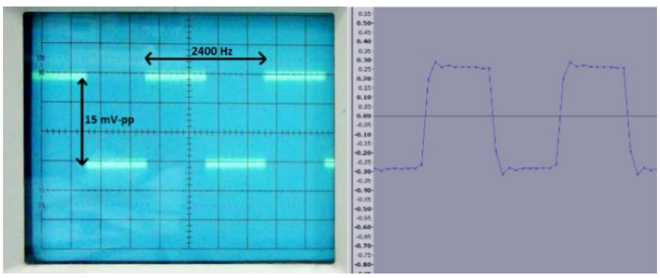
3.3. Fast Fourier Transform Validation

Two kinds of tests were conducted to measure the performance of the implemented FFT algorithm, i.e., the single frequency test and dual-frequency test (intermodulation distortion (IMD) test). The first test was to measure the response of the implemented algorithm to a single frequency between 100Hz– 4100Hz with a 100Hz increment.

The second test was to measure the level of an unwanted combination of different frequencies found in the input signal. The intermodulation distortion test added components to the sound that are not found in the original signal. This effect results from non-linearity in your audio system. For instance, two frequencies, f_1, and f_2 may produce new frequencies i.e. f_2-f_1, f_2+f_1, f_2-2f_1, f_2+2f_1 or any other intermodulation component [18] [19]:

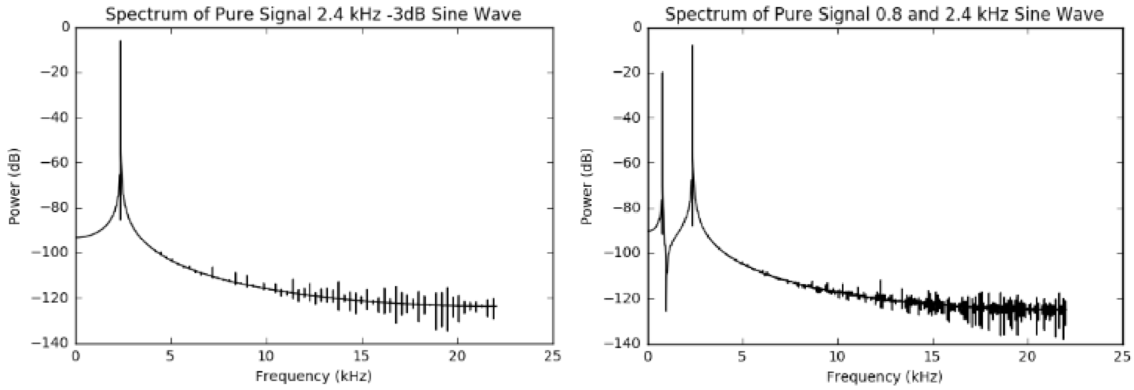
$$m \cdot f_2 \pm n \cdot f_1 \qquad (2)$$

where m and n are integers, when a complex acoustical passage is a source, the IMD can be quite extraordinary.



(a) (b)

Fig. 7. Square wave tests, (a) the input signal; (b) signal read by the instrument.



(a) (b)

Fig. 8. An example of the FFT plot: (a). pure sine wave at 2400Hz; (b). combined sine waves of 800Hz and 2400Hz.

The first test shows that the implemented FFT algorithm is performed well with no distortion and harmonics. The example of the FFT output is shown in Fig. 8(a). The test is conducted with 3 seconds durations wave file with -3dBFS magnitude and the sample rate of the data is 44.1kHz. There is only small harmonics and ripple in a frequency higher than 4.1kHz.

3.4. Method to Indicate a Poor LSWM Test and Improvement to The Procedure

The instrument developed is to predict the E_s of a wood utilizes a microphone. The sensor might pick up unwanted sounds (noise) such as the noise produced by friction between the wood and the supporting base when the wood is tapped too hard. Wood is an anisotropic material where the recorded impulse signal created by the tapping might have more than one frequency resonance. Typically, the f_0 is the frequency component with the highest magnitude. Specific characteristics of the wood require one to inspect the unfiltered spectrum since it might consist of ripples with some unwanted frequency components. The LSWM test procedure, therefore, needs improvement.

A band-pass filter was performed after obtaining the estimated resonant frequency (f_0) of 1480Hz with a cut-off frequency of estimated resonant frequency at $\pm$ 200Hz and 3rd order Butterworth band-pass filter. The filtered signal, with its estimated resonance frequency, is shown in Fig. 9. An envelope fitting is another approach which widely used to determine the damping from a free vibration curve. The decay rate definition of damping may be based on the concept of energy dissipation. If the energy loss is small compared to the stored energy, the amplitude will not decrease very much in one cycle of free vibration, and the motion is very close to being sinusoidal [20].

The procedure is to fit an exponential curve passing through the peaks amplitudes. Though more accurate, the envelope fitting process encounters similar issues with the logarithmic decrement method [21].

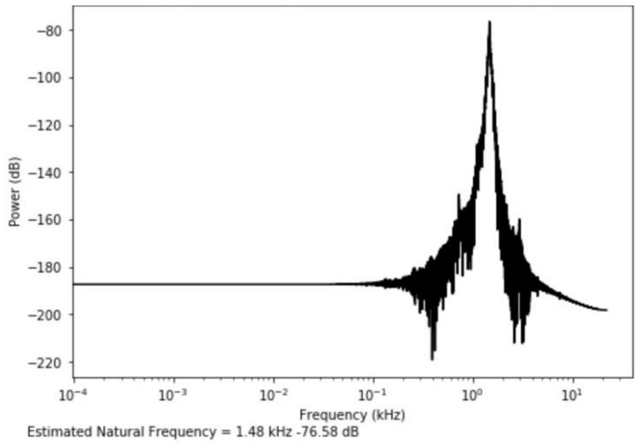


Fig. 9. The filtered Mahogany #1 with 3rd order Butterworth filter, at a resonant frequency of 1480Hz.

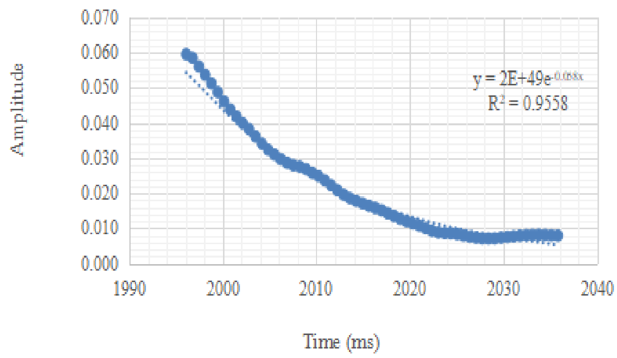


Fig. 10. The envelope fitting result of the Mahogany #1 wood.

The process of the envelope fitting procedure can be described as follows. Data points of 1764 (this number is 1/25 of the sampling rate) were selected from the signal, counted from the highest magnitude. The envelope of the signal was then produced by detecting the following data points that have lower values or peak than the previous ones. Thus, only the peak of the sinusoid signal can pass through the filter. An example of the implementation is shown in the code snippet below.

```
# y is the filtered signal with band pass filter
# y_envel is y-axis value of envelope
# t_envel is x-axis value of envelope
# len is function to calculate the length of a list
y_envel = [y[data] for data in range(len(y)-1)
if (y[data-1]<y[data] and y[data+1]<y[data])]
t_envel= [data for data in range(len(y)-1)
if (y[data-1]<y[data] and y[data+1]<y[data])]
```

Envelope fitting using the same wood samples were done. Since the Mahogany wood is the wood with the highest R^2_{ed} in Table 2, it is not surprising if the envelope of the filtered signal of the mahogany follows the exponential form (see Fig. 10).

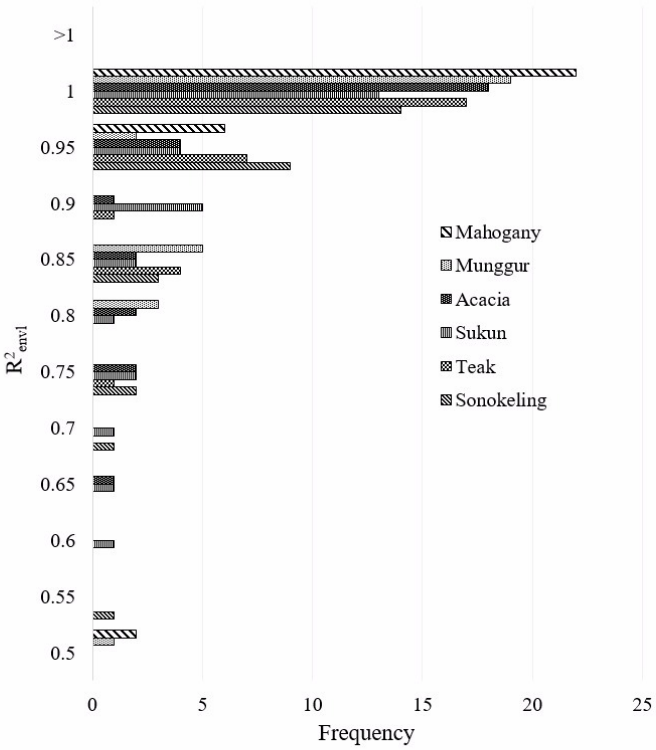


Fig. 11. Histograms of R^2_{envl} of various wood, i.e., Sonokeling, Teak, Sukun, Acacia, Munggur, and Mahogany.

Table 3. The pattern of R^2_{ed} and R^2_{envl}.

Wood Type	***R²ed***	**Percentage *R²envl* > 0.95**
Sonokeling	0.57	46.67 %
Teak	0.59	56.67 %
Sukun	0.63	43.33 %
Acacia	0.90	60.00 %
Munggur	0.90	63.33 %
Mahogany	0.95	73.33 %

The R^2 of the envelope fitting (R^2_{env}) that used the same wood samples were evaluated. Each type of wood consisted of 10 samples, and each sample was run three times through the envelope fitting procedure described above, and the results of histograms showing all the 30 R^2_{env} for each type of wood is shown in Fig. 11.

This result was then tabulated in Table 3 to compare the distribution of correlation between E_d and E_s (called R^2_{ed}) and the percentage frequency of R^2_{envl} occurrence above 0.95 (based on the 30 data for each wood type). The wood with a low R^2_{ed}, such as the Sonokeling (R^2_{ed} = 0.57), tends to have a low R^2_{envl}. In contrast, the wood with high R^2_{ed}, i.e., Acacia, Munggur, Mahogany, tends to have an R^2_{envl} around 0.9. It can be concluded that woods with higher R^2_{ed} have a higher occurrence of $R^2_{envl} > 0.95$. Furthermore, if the R^2 of the envelope fitting shows a weak correlation between the filtered signal and the exponential model, there is a higher indicates that a lot of noise is depicted in the signal, and the LSWM test should be retaken. The result has proven that the R^2_{envl} can be used to measure how well the recorded signal is in representing the longitudinal stress wave.

4. Conclusion

A semi-automatic nondestructive evaluation instrument for predicting the E of wood called MyWood was successfully designed and implemented. Each building block of the device, i.e., the sound card, microphone, and the FFT algorithm, was well performed and validated. In the experiment, the instruments were able to accommodate any waveforms in a range of 800 – 4100Hz, which is within the frequency range of the wood's longitudinal resonant frequency. A novel method to indicate whether the test produced a weak longitudinal stress wave signal data from the LSWM was successfully introduced. The technique involves the conventional LSWM process with additional band-pass signal filtering with resonant frequency as the center frequency of the filter and the envelope fitting method. The longitudinal stress wave data from the preliminary research were able to produce a vital parameter named as R^2_{envl} that indicates whether the data recording procedure of LSWM should be redo or occurrence of environmental noise.

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Balza Achmad, photograph and biography not available at the time of publication.

Ali Awaluddin, photograph and biography not available at the time of publication.

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