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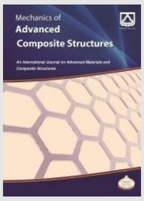

Numerical Optimization of Non-destructive Ultrasonic Testing in Identifying Defects in Composite Structure of Pine Tree Trunk

M. Sheykholeslami [a*], M. Bayat Kazazi [b], A. Amoochi [a] ,
S. Mazdak [c], M. Ghaderi [a], M. Zeighami Salimabad [d]

[a] Department of Mechanical Engineering, Faculty of Engineering, Arak University, Arak, 38156-88349, Iran
[b] Department of Mechanical Engineering K. N. Toosi University of Technology, Tehran, Iran
[c] Department of Mechanical Engineering, Faculty of Engineering, Tafresh University, Tafresh, 3951879611, Iran
[d] Department of Medical Physics, University of Wisconsin-Madison, Madison, WI, USA

KEYWORDS

Ultrasonic test;

Simulation of waves;

Signal-to-noise ratio;

Detection of wood defects.

ABSTRACT

According to the properties of the pine tree trunk and its wide range of applications, finding its defects can play a vital role in reducing costs. Since the ultrasonic test is a non-destructive method, this method is an appropriate alternative to find defects in the pine tree trunks. Optimizing the ultrasonic non-destructive test is necessary because the correct choice of the ultrasonic test affecting factors increases the reliability of the test results. In this paper, at first, a simulation method for non-destructive ultrasonic tests in wooden parts using COMSOL Multiphysics software is presented. Both size and location of the defects have a considerable impact on the signal in the simulation. The defect size has a higher effect on signal amplitude and signal-to-noise ratio changes. So, the location of the defects is detected according to the amplitude of signals received in three points according to the method described in the paper. In the following, using the method of design of experiments, the effect of input factors containing frequency and signal amplitude on responses such as signal-to-noise ratio and loss of signal amplitude has been investigated. Results showed that these have an important effect on the output signal. Finally, the optimal simulation settings have been determined. According to the analysis, if the test frequency is 50 kHz and the amplitude of the input signal is 0.08 mm, the desirability value is equal to 100%, which indicates the high desirability of the ultrasonic test of wooden parts under the mentioned settings.

1. Introduction

Due to high resistance to low temperatures, reasonable price, and durability, pine wood has been used for many years in many industries, including decorations, furniture, home furnishings, wooden poles for the electricity supply network, and construction industries. In these industries, the presence of holes and defects can incur additional costs and make the product defective. Defects in the tree trunk are inevitable because the quality of the wood depends on the conditions and the environment in which the tree grows. Exposure of wooden structures to extreme environmental conditions can also lead to decay, insect damage, and weathering. The average life of wooden structures can vary between 35 and 50 years depending on the type of wood and its surrounding environment [1]. To identify and diagnose defects in wooden structures, various methods are used such as visual inspection, hitting with a hammer, measuring the resistance to the penetration of sharp tools, etc. [2]. Since the mentioned methods not only lead to the destruction of samples but also are not time-saving and cost-saving, providing a non-destructive way to identify the defects of wooden structures can be useful. The ultrasonic test is a non-destructive way that can be used in wooden parts [3].

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* Corresponding author. Tel.: +98-86-32625722; Fax: +98-86-32774031
E-mail address: m-sheykholeslami@araku.ac.ir

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Dikrallah et al. [4] experimentally measured the propagation speed of ultrasonic waves along anisotropic wooden beams. They applied the ultrasonic wave as a mechanical shock to the wooden beam and on the opposite side, the arrival time of this wave was measured by the ultrasonic sensor. By conducting experiments, they found that the speed of propagation and the time of the first response is a function of the wave propagation direction and the anisotropy of the wood. They also showed that the radial, tangential, and longitudinal elastic coefficients are different from each other, which causes the difference in wave speed in different directions. Tallavo et al.[5] investigated the defects in pine tree trunks experimentally and numerically. They considered wood as an orthotropic material. Due to the orthotropic property of wood, the stress wave propagation speed varies in different directions and the presence of defects can also affect the stress wave propagation speed. Tallavo et al. developed a new method to evaluate the condition of wooden beams using the ultrasonic test. This method was based on the numerical simulation of the propagation of ultrasonic waves in an orthotropic cylindrical environment, which provided the possibility of estimating the elastic modulus in the radial and tangential directions, as well as the probability density function of the wave speed. The frequency range used in these tests is between 30 and 70 kHz, and the amplitude of the waves used is about hundredths of a millimeter. Also, in this research, the transmitted waveform was measured at five different angles (±90, ±135, and 180) relative to the position of the transmitter [2].

Espinosa et al. [6] evaluated the effect of wood anisotropy conditions on the time of flight of ultrasonic waves using the ray tracing method. In this research, wooden samples were divided into two groups without defects and with defects, and the frequency used in the tests was considered equal to 60 kHz. This method states that the orthotropic property of wood in the radial-tangential plane changes the shape of the wave propagated in the wood and turns the path that the wave travels into a curve. Ray tracing approximation using the wavefront construction method provides the possibility of simulating wave propagation in orthotropic environments and therefore enables the calculation of flight time estimates in defective and defect-free states. Mousavi et al. [7] presented an effective method for detecting hole defects in wood using empirical mode decomposition analysis. In this method, an ultrasonic wave with 54 kHz frequency, was applied on rectangular wooden samples. The output signal was decomposed into its constituent states using empirical mode decomposition. This process decomposes a nonlinear wave signal into its quasi-orthogonal bases known as intrinsic mode functions. Then the matrix of all the intrinsic state functions is collected, and its covariance matrix is extracted. Also, by conducting several studies, this research found that the maximum eigenvalue of the proposed covariance matrix compared to other factors such as the time of flight can detect the defects inside the wood due to its greater sensitivity.

Sallehuddin et al. [8] used an ultrasonic test with a frequency of 40 kHz to detect and analyze defects in wood. They used two ultrasonic transducers, which were placed in front of each other and on both sides of the wood. One of them is the transmitter and the other transducer is the receiver of ultrasonic waves. By using analyses based on signal-to-noise ratio and cross-correlation, the elastic modulus of wooden samples was evaluated in the longitudinal direction. Their results showed that the ultrasonic system used can distinguish perfect wood from defective wood. Vaclav et al.[9] investigated elastic waves in wood using finite difference time domain numerical simulation. Using a two-dimensional code in a cylindrical coordinate system and considering wood anisotropy, they simulated elastic waves in ANSYS software and found that the number and size of growth circles affect wood anisotropy. Lin et al. [10] 2016 proposed a detecting method inside and onside(decay) problems of wood by evaluating the speed of the wave in the sample based on their previous results that the properties of wood can affect wave velocity. Li et al. [11] designed a new non-destructive test setup by using three signal analysis techniques (peak time - cross correlation - stress wave signal) to find defects in the wood samples. They reported that this method was efficient in finding small holes. Taskhiri et al. [12] reported that usual factors such as wave speed and TOF in non-destructive testing of wood may not be able to detect wood defects independently under all circumstances, but by changing the signal amplitude, the wood sample test in all situations can be performed. Vössing et al. [13] found that because of the lack of contact between transmitter and receiver with the wood sample, UT tests by an air-couple setup increase the accuracy. In addition, this method also produces more reliable results. Mousavi et al. [14] achieved 100% accuracy in the lab and 92% in field tests by using several artificial intelligence algorithms and classification of previous tests' information.

According to the mentioned literature, the researchers have used different frequencies and amplitudes to evaluate and simulate the ultrasonic test in wooden parts. There are no comprehensive reports about the reason for choosing these settings and their optimization. In this paper, the numerical approach has been exploited to optimize the ultrasonic non-destructive test setup for defects detection of pine tree trunks, using the desirability function approach. For this purpose, a simulation of the ultrasonic test was performed in COMSOL Multiphysics software, and by using statistical methods, the effects of frequency and amplitude of the transmitted waves were studied without holes and with holes. Finally, the optimal frequency and amplitude of the ultrasonic wave have been proposed based on the desirability function approach.

2. Numerical Simulation

The plane strain assumption[6] was considered in the pine tree trunks ultrasonic tests simulation. COMSOL Multiphysics commercial software has been exploited for numerical simulation. In the following, the simulation steps of this process are described in detail.

2.1. Modeling

In simulations, the two-dimensional model was exploited for the pin tree trunk modeling, and therefore the plane strain assumption was considered in the numerical study. Figure 1 shows two models without holes and with holes (defects) that were used in the simulation, and Table 1 presents the geometric dimensions.

2.2. Material Properties

As mentioned, pine wood is used in this simulation. This wood is anisotropic due to vascular tissue, growth rings, and defects caused by insects, fungi, and weather conditions. Therefore, in this simulation, wood is modeled as an orthotropic material. Table 2 shows the properties used in the simulation. It should be noted that z is the perpendicular direction to the plane, r is the radial direction, and θ is the circumferential direction.

Table 1. Geometric dimensions of the model.

Parameter	Size (mm)
The diameter of the tree trunk	200
The diameter of the hole	60
The eccentricity of the hole	40

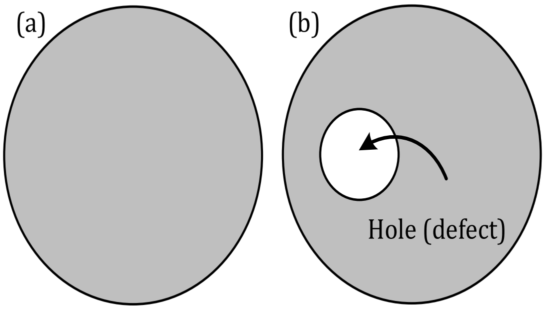


Fig. 1. (a) Without a hole, (b) With a hole (defect) Models.

2.3. Boundary Condition

The model is divided into several parts to apply the boundary conditions in this simulation. As can be seen in Fig. 2, all the degrees of freedom in boundary region 1 are limited, and in boundary region 2, vertical displacement was applied according to Eq (1).

$$u_y = A sin(2\pi f t).rect() \qquad (1)$$

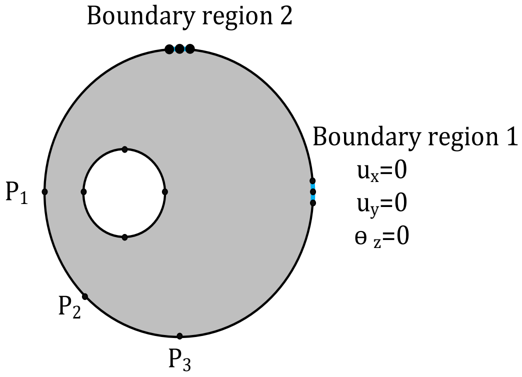


Fig. 2. Boundary conditions applied in the simulation.

The movement of each boundary region can act like a transmitter and create an ultrasonic wave inside the wood. The characters of the generated wave can be adjusted by changing the displacement parameters of the moving wall in boundary conditions. Regarding Eq (1), u_y is the vertical displacement signal, A is the displacement signal amplitude, f is the frequency, t is the time, and rect () is the rectangular wave function. Also, in Fig. 3(a), the rectangular wave function is shown, and in Fig. 3(b), the vertical displacement signal in the frequency of 50 kHz and the amplitude of 0.05 mm is shown.

Table 2. Mechanical properties of pine tree [15].

Density ($\frac{kg}{m^3}$)	Elastic modulus (GPa)			Poisson's ratio			Shear modulus (GPa)		
	E_r	E_θ	E_z	ϑ_r	ϑ_θ	ϑ_z	G_r	G_θ	$\mathbf{G_z}$
491	11.3	9	16.4	0.043	0.063	0.024	0.79	9.1	11.8

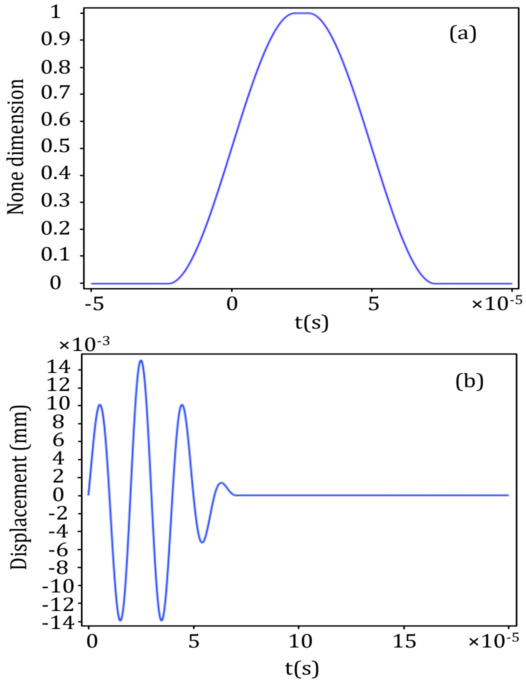


Fig. 3. (a) Rectangular function. (b) Vertical displacement

2.4. Mesh

The mesh size should be at least one-tenth of the wavelength to obtain accurate results of ultrasonic wave simulation [11]. In this simulation, to improve the results and increase the accuracy, the mesh size was one-twentieth of the wavelength. Figure 4 shows the meshing in the states without holes and with holes, which were meshed by the first-order triangular mesh. If the frequency is 70 kHz, the model without holes has 2578 elements, and the one with holes has 2384 elements.

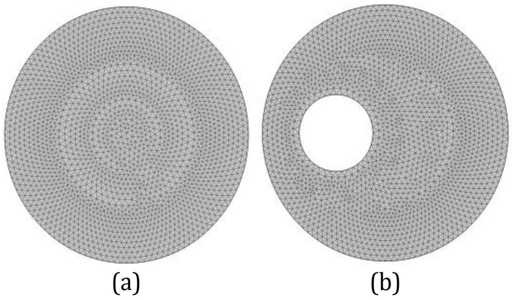


Fig. 4. Meshing. (a) Without a hole. (b) With holes.

2.5. Method

Since ultrasonic waves are mechanical waves, solid mechanical physics and time-dependent solutions of COMSOL Multiphysics have been used in simulation. The simulation time is 50 times larger than the ultrasonic wave period, and the simulation was done in steps of one-tenth of the period.

Figure 5 shows the displacement contour at different times with a frequency of 50 kHz and an amplitude of 0.05 mm in the states without holes and with holes. As it was presented in Fig. 5, when the ultrasonic wave reaches the hole area, the displacement distribution is different from the case without the hole.

3. Simulation Plan

In the simulation of non-destructive ultrasonic testing in wooden parts, it is predictable the frequency and amplitude of the displacement of ultrasonic waves have a considerable influence on the test results. The statistical approach based on the numerical simulation has been exploited in this paper to study the effect of mentioned parameters. Simulations were planned based on a full factorial design method to check the effectiveness of these input factors.

A summary of the full factorial design and the levels of control factors used are presented in Table 3. As can be seen in this table, the number of tests required in this design is equal to nine tests, and for doing two cases, without holes and with holes, the total number of simulations required is equal to eighteen. Level parameters were selected based on usual parameters in ultrasonic tests of wood parts.

In the following, by determining the tests, the displacement changes were measured at three points P1 to P3 (according to Fig. 2).

Figure 6 shows an example of received signals in different settings at three points P1 to P3. It can be seen that in the presence of the hole, the received signal has been changed.

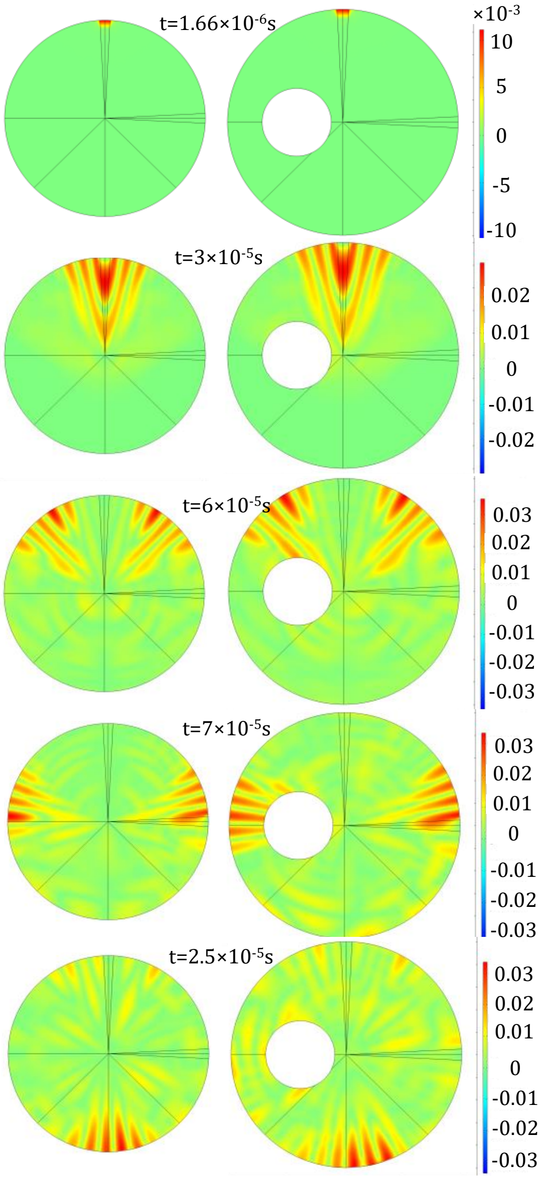


Fig. 5. Variations of the displacement contour in the model without holes and with holes.

4. Results

To evaluate the results, the time signals obtained from the simulation were processed. Also, the two components of the geometric average of the signal-to-noise ratio at points P1 to P3 and the geometric average of the loss of signal amplitude at points P1 to P3 and in two states (without holes and with holes) were considered as the results.

4.1. Signal-to-noise Ratio

The signal-to-noise ratio is an important parameter for evaluating the quality of the ultrasonic test. By increasing this ratio, the signal obtained from the ultrasonic test has a higher quality and capability to precisely detect the peaks of the signal from the noises created. In the simulation of the ultrasonic test of wooden parts, since the output signal is measured at three points (P1, P2, and P3), as a result, the signal-to-noise ratio should be at its maximum value at these three points and for two states (without holes and with holes). To calculate the signal-to-noise ratio, first, the signal(echo) is smoothed by the Savitzky-Golay filter[16], and then the noise is separated from the original signal. Figure 7(a) shows the filtered echo, and Figure 7(b) shows the original signal. In the following, the signal-to-noise ratio can be calculated by Eq (2) [17].

$$SNR = 20\,log(\frac{RMS_{signal}}{RMS_{Noise}}) \qquad (2)$$

In Eq (2), SNR is the signal-to-noise ratio, RMS_{signal} is the Root mean square of the signal, and RMS_{Noise} is the Root mean square of the noise. In the following, the signal-to-noise ratio was calculated at points P1 to P3 and in two states without holes and with holes. Table 4 shows the ratio of signal-to-noise in different frequencies and amplitudes of simulation.

4.2. Loss of Signal Amplitude

The loss of signal amplitude is another parameter to evaluate the quality of the ultrasonic test. The ratio of the maximum value of the obtained signal amplitude to the maximum value of the initial signal amplitude is used to calculate the loss of the signal amplitude. The higher ratio leads to a better quality of the output signal and no signal loss. In the simulation of the ultrasonic test of wooden parts, since the output signal is measured at three points (P1, P2, and P3), the changes in amplitude loss should be at their maximum value at these three points for two states (without holes and with holes). Table 5 shows the ratio of signal amplitude loss in different simulation frequencies and amplitudes.

4.3. Analysis of Results and Desirability Function

The statistical analysis using Minitab software was performed to investigate the effectiveness of the two mentioned evaluation factors at points (P1 to P3) in two cases (without holes and with holes) on the quality tests. According to Fig. 8(a), the two factors of frequency and amplitude of the initial signal affect the signal-to-noise ratio with a probability of 95 percent and affect the amplitude loss ratio of the primary signal with the same probability, according to Fig. 8(b).

Table 3. Full factorial design and levels of factors.

Levels Factors name	Level 1	Level 2	Level 3	Number of tests	Number of states	Total number of tests
Frequency (kHz)	30	50	70	9	2 modes (without holes and with holes)	18
Displacement signal range (mm)	0.02	0.05	0.08			

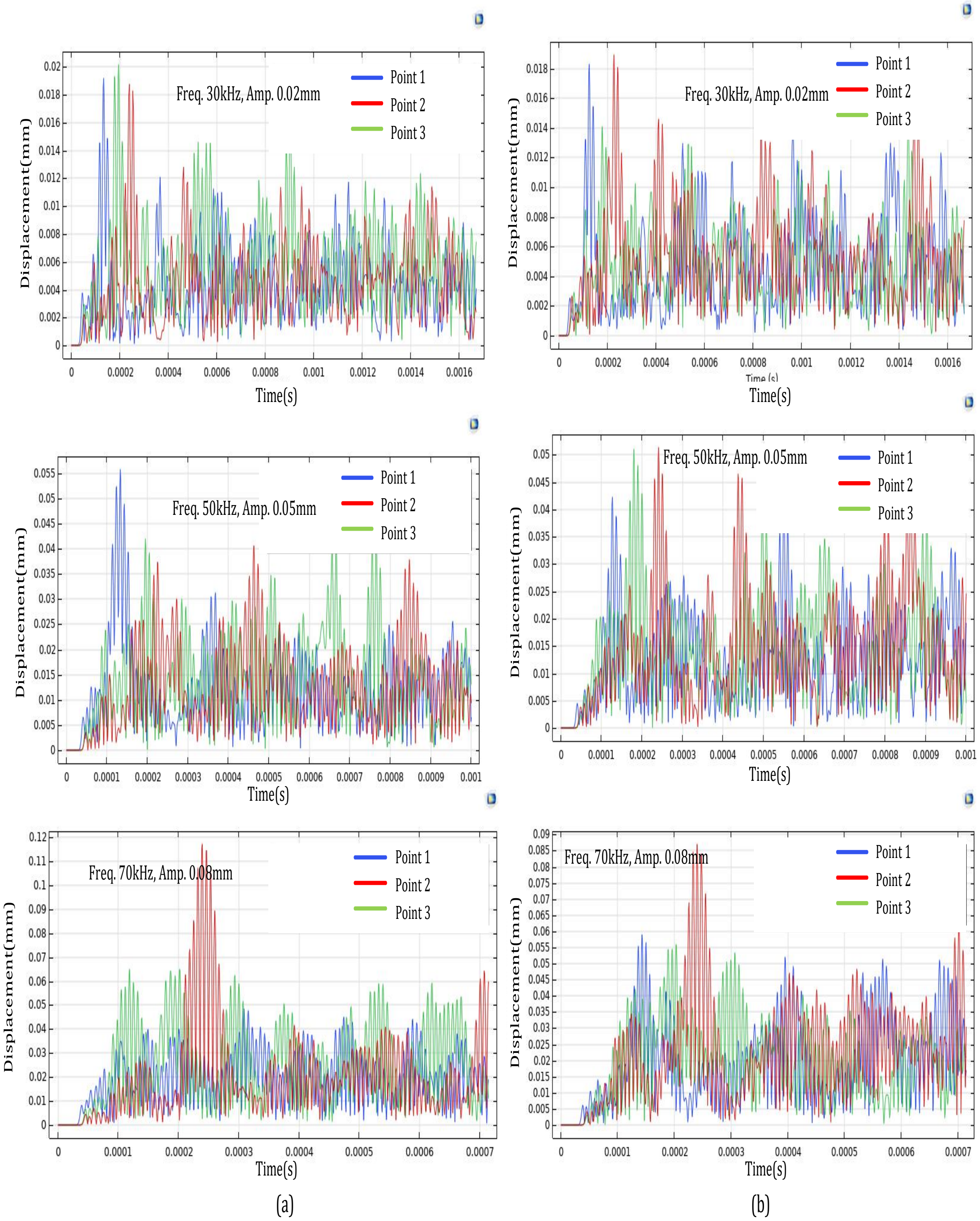
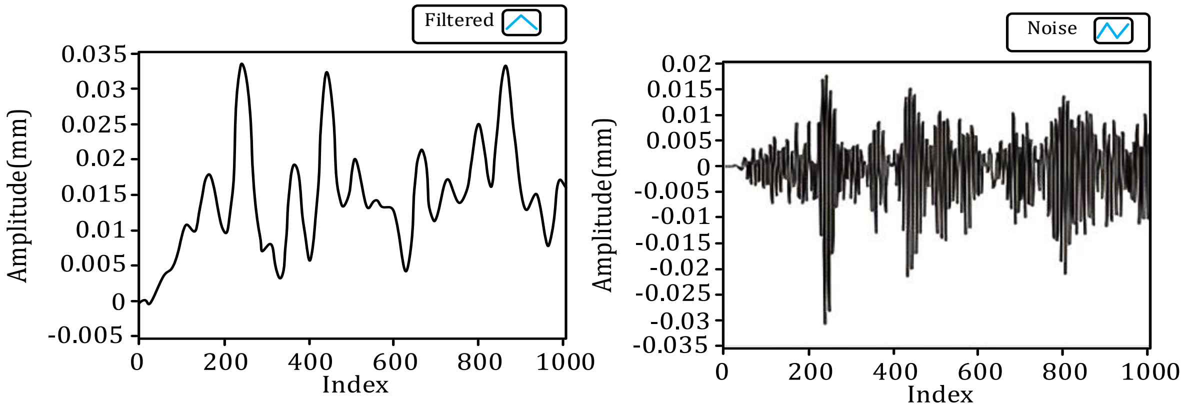


Fig. 6. Signals obtained in 3 points in simulations with different settings. (a) Without a hole. (b) With a hole.



(a) (b)

Fig. 7. (a) Filtered signal. (b) noise resulting from the signal.

Table 4. Signal-to-noise ratio in different simulation conditions (dB).

		Without hole			With hole			Geometric average without holes	Geometric average with holes	Overall geometric average
Amplitude Frequency		0.02 mm	0.05 mm	0.08 mm	0.02 mm	0.05 mm	0.08 mm			
30 kHz	P1	6.912	7.610	7.664	7.814	9.072	9.210	6.835	7.682	7.246
	P2	7.205	7.761	7.811	7.624	8.203	8.428	7.693	8.514	8.093
	P3	6.411	7.709	7.880	7.609	8.292	8.565	7.784	8.728	8.243
50 kHz	P1	8.450	9.449	9.449	7.374	8.079	8.079	7.935	7.819	7.887
	P2	7.604	8.287	8.287	8.156	8.671	8.671	8.593	8.502	8.547
	P3	7.774	8.104	8.104	7.950	8.771	8.771	8.593	8.502	8.547
70 kHz	P1	8.049	8.274	8.274	8.275	8.850	8.850	7.817	8.273	8.041
	P2	7.967	8.263	8.263	8.332	9.155	9.155	8.267	8.810	8.534
	P3	7.448	8.263	7.423	8.211	8.439	8.439	7.976	8.810	8.383

Table 5. The ratio of signal amplitude loss ratio ($\frac{A}{A_0}$) in different simulation conditions.

		Without hole			With hole			Geometric average without holes	Geometric average with holes	Overall geometric average
Amplitude Frequency		0.02 mm	0.05 mm	0.08 mm	0.02 mm	0.05 mm	0.08 mm			
30 kHz	P1	0.960	0.960	0.951	0.951	0.915	0.916	0.969	0.848	0.906
	P2	1.009	1.009	0.999	0.704	0.704	0.706	0.993	0.848	0.918
	P3	0.939	1.012	1.014	0.946	0.946	0.966	0.987	0.855	0.919
50 kHz	P1	1.026	1.115	1.115	0.781	0.845	0.845	0.868	0.932	0.899
	P2	0.834	0.839	0.839	1.009	1.021	1.021	0.888	0.960	0.923
	P3	0.763	0.747	0.747	1.026	1.027	1.027	0.887	0.960	0.923
70 kHz	P1	0.480	0.500	0.498	0.755	0.737	0.737	0.842	0.806	0.824
	P2	0.854	0.812	0.812	0.694	0.699	0.699	0.841	0.824	0.832
	P3	1.455	1.464	1.464	1.001	1.088	1.088	0.840	0.824	0.832

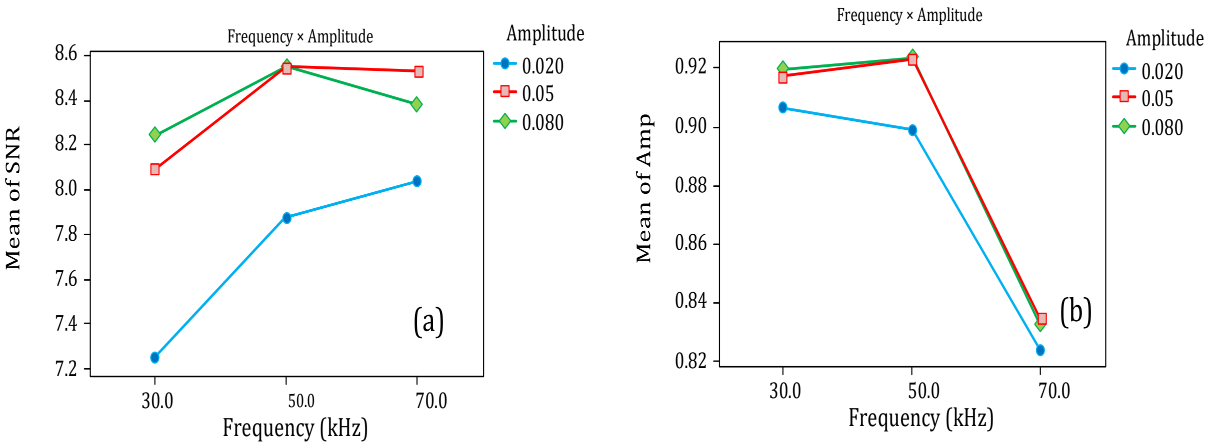


Fig. 8. Statistical analysis charts from Minitab software: (a) Analysis of the ratio of the noise. (b) Amplitude loss ratio analysis.

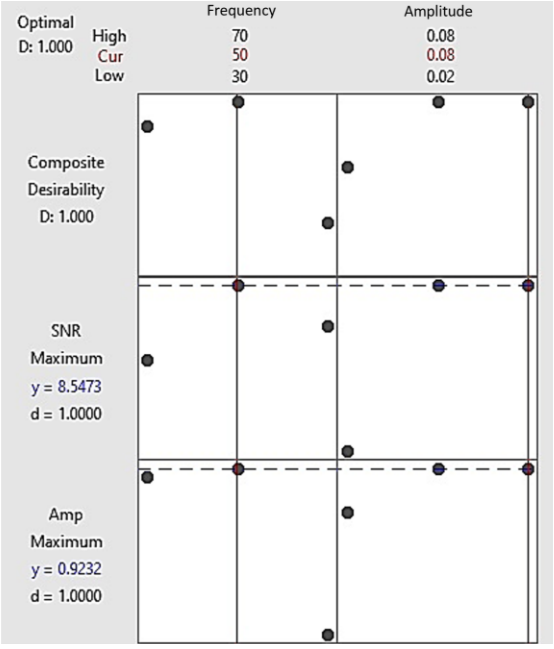


Fig. 9. The result of the desirability function approach.

5. Conclusion

In this paper, a numerical study was done to determine the optimum initial parameter setting in the ultrasonic test of wood parts. At first, a simulation method of non-destructive ultrasonic evaluation of pine tree trunk wood was presented. Besides, the design of experiments (DOE) method was used for planning simulations to study the effect of two initial parameters (amplitude and frequency of input signal) on the test results.

Results show that the two initial parameters of the frequency and the amplitude of the initial signal, on the two evaluation factors of the geometric average of the signal-to-noise ratio and the geometric average of signal amplitude loss in two cases (without the hole and with the hole) is effective with 95% probability.

Next, to determine the optimal settings for the ultrasonic test of wooden parts, the desirability function was used. According to the results obtained from this approach, if the frequency set to 50 kHz and the amplitude of the initial signal is to be 0.08 mm, the desirability value is equal to 100%, which indicates the high desirability of the ultrasonic test of wooden parts under the mentioned settings.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors have entirely observed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

Nomenclature

D_t	The diameter of the tree trunk
D_h	The diameter of the hole
E_h	The eccentricity of hole
u_y	Vertical displacement signal
A	Displacement signal amplitude
f	Frequency
t	Time
rect ()	Rectangular wave function
z	Perpendicular direction to plane
r	Radial direction

θ	Circumferential direction
E_r	Elastic modulus in r direction
E_θ	Elastic modulus in θ direction
E_z	Elastic modulus in z direction
ϑ_r	Poisson's ratio in r direction
ϑ_θ	Poisson's ratio in θ direction
ϑ_z	Poisson's ratio in z direction
G_r	Shear modulus in r direction
G_θ	Shear modulus in θ direction
G_z	Shear modulus in z direction
SNR	Signal-to-noise ratio
RMS_{Signal}	Effective value of the signal
RMS_{Noise}	Effective value of the noise

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