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The Identification of Optimal Frequency for Ultrasonic Transducers in Concrete-Defect Detection using COMSOL® Simulator

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Abstract: Ultrasonic testing for concrete evaluation is a non-destructive method that uses high-frequency acoustic waves to identify internal defects in concrete structures. This study aims to determine the optimal frequency for ultrasonic transducers in detecting defects in concrete structures. Simulations were conducted using COMSOL Multiphysics® software. The research involves designing, simulating, and analyzing a concrete model with various defects to evaluate the performance of different ultrasonic frequencies. A two-dimensional (2-D) concrete model was simulated, with three different types of defects introduced to assess their impact on the arrival time of ultrasonic signals. The simulation integrated pressure acoustics, solid mechanics, electrostatics, and electric circuit modules, with precisely defined material properties and meshing parameters. Results indicated that frequencies of 200 kHz and 500 kHz showed the highest sensitivity to defects. However, 200 kHz was identified as the optimal frequency due to its balance between sensitivity and energy loss. This frequency effectively distinguished individual defects and represents a reliable method for defect detection in concrete structures.

Keywords: COMSOL simulation, concrete, defect, frequency, ultrasonic

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1. INTRODUCTION

Concrete is the most reliable man-made material widely used in the construction industry. In Malaysia, concrete structures persist as the most common type of building structure due to their flexibility, durability, low construction cost, and the availability of high-quality raw materials [1], [2]. According to the Department of Statistics Malaysia (DOSM), in 2022, the production of cement reached approximately 19.86 million metric tons. This concrete raw material is produced to build the nation's growing infrastructure. However, due to its brittle nature, concrete is vulnerable to damage and degradation. This includes cracking, corrosion, and the formation of air holes. These issues are more likely to occur when quality assurance during construction is not properly monitored. These discontinuities can lead to structural failure when reaching critical sizes, which may cause significant loss of life and property. Hence, a proper evaluation of concrete structures' quality and long-term performance is vital from both safety and cost perspectives. Early detection of defects is crucial to prevent damage and preserve the structural integrity of affected concrete components.

Ultrasonic pulse velocity (UPV) is a reliable and widely accepted non-destructive method for evaluating the integrity of concrete structures. It involves placing a pair of ultrasonic transducers at a specific distance to record the time taken by acoustic waves to propagate through a medium, which provides information about the internal condition of the object under test (OUT). In general, increased travel time may indicate potential structural deterioration, while reduced travel time generally correlates with minimal or no defects [3].

In evaluating data for transmission mode, parameters such as amplitude and time-of-flight are critical considerations. Furthermore, the excitation frequency for ultrasonic transducers in assessing concrete structure is a significant aspect that requires attention. However, limited studies have focused on investigating the optimal frequency for ultrasonic testing. Previous research conducted by Jeongnam et al. [4] utilized Finite Element Analysis (FEM) to detect vertical cracks in concrete. The frequency used in their study is 65 kHz. In 2018, Pahlavan et al. [5] used the pulse-echo method with transducer frequencies of 60 kHz and 150 kHz to investigate the effect of crack distance on the arrival time. A year later, Vuong and Nguyen [6] analyzed the effect of ultrasonic frequencies on the attenuation of wave amplitudes using two frequencies, 50 kHz and 100 kHz. Results indicated that ultrasonic waves with high frequency can identify defects in concrete structures. However, there is still room for identifying the optimal excitation frequency for detecting internal defects in concrete structures, which has not been validated in previous studies.

While real-world concrete is often heterogeneous, this study assumes concrete to be a homogeneous material to provide a controlled and idealized foundation for simulation and defect detection analysis. Homogeneous concrete serves as a simplified model that allows for the initial validation and optimization of ultrasonic testing methods [7]. Despite its limitations, such an approach is commonly adopted in simulation-based studies to minimize the influence of complex variables and to obtain reliable baseline results. The findings from homogeneous material studies can thus provide useful benchmarks for developing more reliable detection techniques applicable to real and complex heterogeneous concrete structures. Nevertheless, it is important to note that the presence of aggregates, voids, and varying pore distributions in heterogeneous concrete may affect wave propagation, including phenomena such as scattering, reflection, and mode conversion. These factors can potentially influence both time-of-flight and amplitude readings, which may impact the accuracy of defect detection. Future research is recommended to expand on these findings by adopting heterogeneous concrete models to evaluate the real-world applicability and reliability of the identified optimal frequency.

This paper aims to identify the optimal frequency for ultrasonic transducers in detecting defects in concrete structures using the percentage of maximum relative error method.

2. METHODS

2.1 2-D Concrete Modelling

The design, simulation, and analysis of the concrete model for defect detection were conducted using COMSOL Multiphysics software version 5.6. The simulation incorporated various physics modules, including pressure acoustic, solid mechanics, electrostatics, and electric circuit modules.

In this study, a two-dimensional (2-D) model has been utilized to reduce the simulation time, as it simplifies the geometry while still preserving the key features of wave propagation in concrete. The 2-D model was divided into three different domains, as shown in Figure 1. The concrete block domain followed a standard cross-sectional size of 300 mm × 300 mm, in line with common industry specifications [8], [9]. Although concrete is a heterogeneous and multiphase material, it is simplified as a homogeneous material in this study. This assumption reduces computational complexity by excluding the influence of aggregate characteristics on the mechanical behaviours of the concrete material. However, in this paper, the term ‘homogeneous concrete’ refers to non-defective concrete or clean concrete with no defects, whereas ‘inhomogeneous concrete’ refers to defective concrete or concrete with the inclusion of defects.

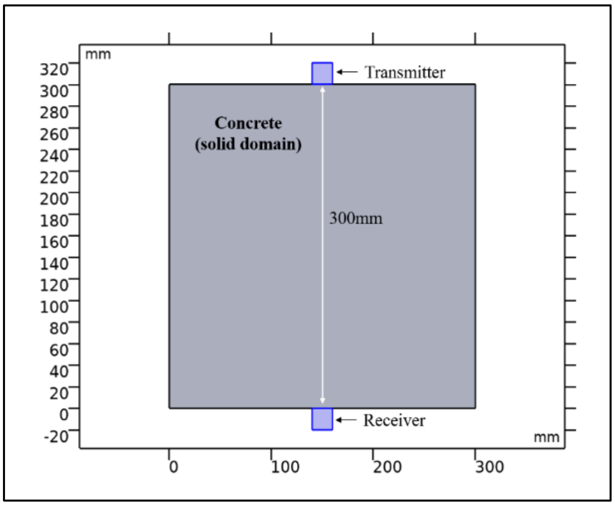

Figure 1. Schematic diagram of the 2-D geometry for the homogeneous concrete model.

Other block domains, each with a diameter of 20 mm, were placed on the top and bottom surfaces of the concrete model to act as the transmitting and receiving transducers. The transmitter was connected to an electrical circuit and excited by a pulsed electrical signal, while the receiver captured the propagated wave. Both transducers were spaced 300 mm apart, consistent with the size of the concrete block [10], to enable wave transmission using the through-transmission method.

For the defective concrete model, three distinct defects were included to investigate the arrival time of received ultrasonic signals. A circular domain was added in the concrete model to represent an air hole or rust, and a rectangular domain was included to represent an air-filled crack. All defects were centrally located within the geometry to ensure consistent interaction between the acoustic waves and the defects. This configuration also minimizes boundary-related artefacts and focuses the analysis on material response alone. The diameters of these defects, obtained from a previous paper [6], are tabulated in Table 1. For a crack, the diameter refers to its length. The corresponding models are illustrated in Figure 2.

Table 1. Diameter of defects included in the concrete model

Type of defect	Diameter (mm)
Air hole	30
Crack	10
Rust	30

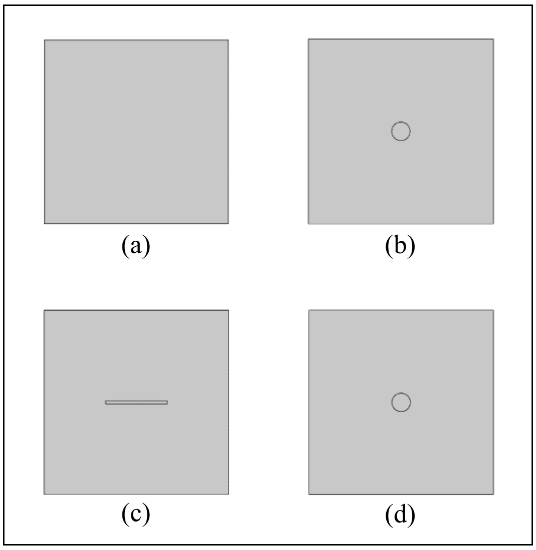

Figure 2. 2-D concrete model: (a) homogeneous concrete, (b) concrete with an air hole, (c) concrete with a crack, and (d) concrete with rust

In this study, each defect type was modelled independently to isolate and examine its unique influence on ultrasonic wave behaviour. This approach enables clearer identification of defect-specific signal responses and arrival time variations. While combinations of defects may occur in practice, simulating them was beyond the scope of this study, which focuses on determining optimal frequencies based on distinct defect interactions. Future work may consider extending the analysis to more complex scenarios involving multiple simultaneous defects.

This study applied the ultrasonic through-transmission method, with the receiving probe positioned at the bottom surface of the concrete model to detect signals emitted from the transmitter. This method was chosen as it directs the pulse energy at a right angle to the transmission path, which facilitates accurate and straightforward measurement of the propagated waves [11].

2.2 Materials Properties

Once the physical model has been constructed, each domain must be defined based on its material properties. Table 2 summarizes the density, Poisson ratio, Young's modulus, and sound speed of the materials used in this study, which directly influence wave propagation behaviour. The data utilized are sourced from a previous study [12].

Table 2. Parameters used in the COMSOL simulation for each material

Material	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Speed of sound (m/s)
Concrete	2000	3500	0.2	3400
Air	-	-	-	343
Rust	3925	102	0.15	5890

A pair of piezoelectric transducers made up of lead zirconate titanate (PZT-5H) was selected as the sensing element. Piezoelectric transducers are widely used for ultrasonic monitoring due to their cost-effectiveness, compact size, and wide frequency range [13]. These transducers convert electrical energy to mechanical energy and vice versa. They work by converting structural vibrations into electrical outputs. Specifically, the piezoelectric material, when subjected to mechanical pressure, generates a voltage waveform as an electrical output. This waveform corresponds to the intensity and frequency of the mechanical input.

2.3 Excitation Pulse

The applied voltage triggered the PZT-5H transducers to generate mechanical vibrations. These transducers were connected to an external circuit using the Terminal feature, which enables the excitation of ultrasonic pulses. This setup allows for the accurate transmission of ultrasonic waves. As illustrated in Figure 3, one surface of the PZT-5H is grounded, while the other surface uses an external terminal (Terminal 1) to access the circuit.

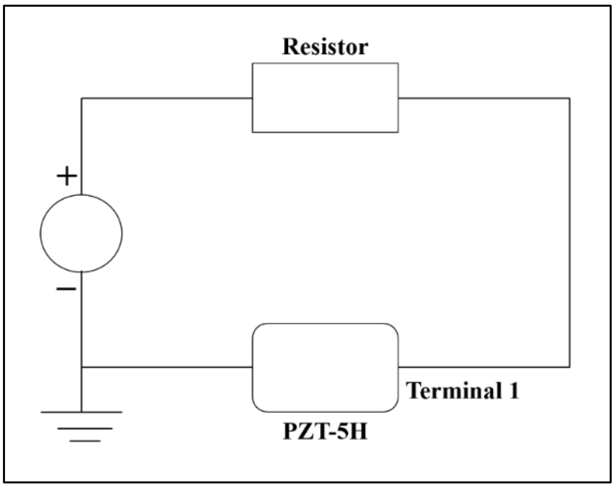

Figure 3. The circuit for driving the PZT-5H.

To measure the output voltage signals, grounding and output terminals were positioned on the top and bottom surfaces of the second PZT-5H. The PZT-5H transducer was excited using two types of signals: a continuous sinusoidal signal (Figure 4) and a pulse signal (Figure 5).

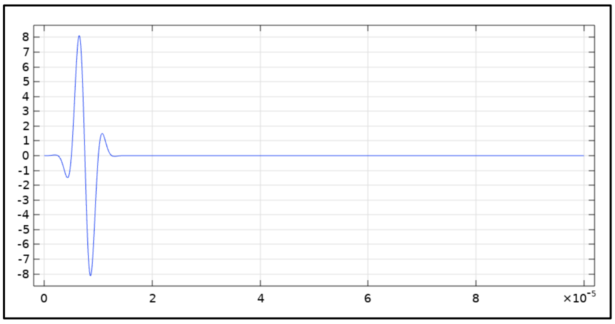

Figure 4. The continuous sinusoidal signal.

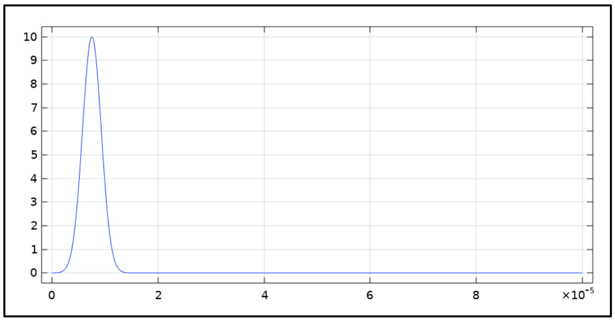

Figure 5. The pulse signal.

The expressions for the previously mentioned signals are described by the following equations:

(a) Continuous sinusoidal signal:

$$V(t) = V_0 \sin(2\pi f t) \tag{1}$$

(b) Pulse signal:

$$V(t) = V_0 \, e^{-\left[\frac{(t-T_0)}{T_0/2}\right]^2} \tag{2}$$

$$T_0 = \frac{1}{f_0} \tag{3}$$

where $V(t)$ and V_0 represent the voltage source signal and its amplitude, respectively. f and f_0 are the source frequencies of the continuous sinusoidal and pulse signals. T_0 is the source period of the pulse signal, and t is the total testing time.

2.4 Meshing and Solving

Meshing creates a discretized representation of the geometry used by the solver during calculations. In this study, each domain of the model was subdivided into small triangular finite elements. A finer mesh enhances computational accuracy, particularly in regions of interest, but increases computational time significantly due to the higher number of elements involved. Therefore, an optimal mesh density was chosen to balance accuracy and computation time.

Besides meshing, the time step setting is significant for solving the finite element model. It is an important factor in achieving high resolution and improving computational accuracy. Furthermore, the time step is related to the signal source period. In this study, the integration time step was set to 1/20 of the source period to ensure sufficient resolution of wave propagation. The average analysis time for this configuration was approximately 1 hour. A time-dependent solver was used to extract time information from the simulation models. The simulation was then initiated by selecting the ‘Solve’ button.

2.5 Determination of Arrival Time

The simulation output from COMSOL Multiphysics was exported as a text file and analysed using Microsoft Excel to identify the arrival time of the ultrasonic signal in the concrete structure. In Microsoft Excel, the received ultrasonic signals were plotted to visualize the amplitude variations. The arrival time was determined by pinpointing the first arriving peak in the measured signals. This first peak represents the earliest direct wave that reaches the receiver after traveling along the path. It is typically used in ultrasonic testing as the arrival time because it precedes any reflections or harmonics. This approach is commonly applied in literature for reliable arrival time detection [4]. An example of this identification process is shown in Figure 6.

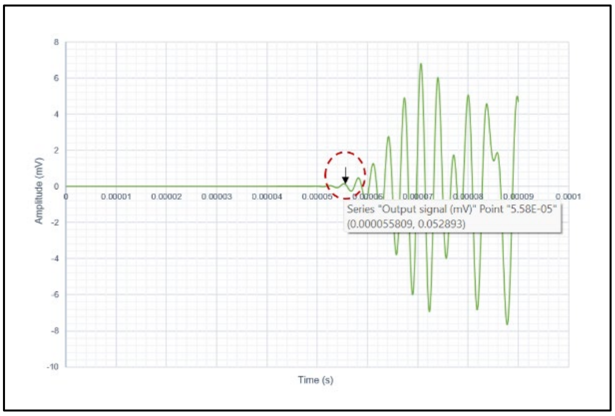

Figure 6. Determining the arrival time of the received ultrasonic signal.

2.6 Optimal Frequency Selection

Five different frequencies were compared to determine the optimal frequency for this study: 20 kHz, 50 kHz, 100 kHz, 200 kHz, and 500 kHz. These frequencies were chosen based on the findings of previous scholars [4], [14]–[17].

To quantify the differences between the evaluated frequencies, the percentage of maximum relative error, δ, of the arrival time in defective concrete with respect to the arrival time in homogeneous concrete, as determined by Equation (4), will be computed. The identification of the optimal frequency is based on how well each evaluated frequency distinguishes individual defects in the concrete structure, as measured by the percentage maximum relative error.

$$\delta = \frac{t - t_0}{t_0} \times 100\% \tag{4}$$

where t is the measured time in defective concrete, and t_0 is the reference time measured in homogeneous concrete.

3. RESULTS

The arrival time of ultrasonic signals in concrete for all different cases and frequencies used is tabulated in Table 3.

Table 3. Arrival time of ultrasonic signals in concrete structure using multiple frequencies.

Frequency (kHz)	Arrival time (μs)			
	t_0	t		
	Homogeneous concrete	Concrete with air hole	Concrete with crack	Concrete with rust
20	167.59	169.72	172.21	168.74
50	125.13	126.64	132.74	125.60
100	91.45	99.64	104.71	93.41
200	51.61	58.93	75.13	58.72
500	44.70	49.76	54.40	49.59

The results demonstrate distinct changes in the arrival time for inhomogeneous concrete compared to homogeneous concrete across all five frequencies. As shown in Table 3, the arrival time of concrete with a crack recorded the longest delay in arrival time. This is likely due to the transverse orientation of the crack, which obstructs the wave path more significantly. In particular, high arrival times are associated with the known defects inhibiting the wave path. This behaviour is expected, as internal flaws in concrete are recognized to increase arrival time due to wave scattering effects [18], resulting in the uncompact structure in some areas. Ultrasonic waves encountering defects undergo scattering, reflection, and significant attenuation [19], [20], causing them to bypass the defects and change the original propagation path.

From a theoretical perspective, the interaction between ultrasonic waves and defects within a concrete medium is determined by complex wave propagation phenomena. When ultrasonic waves travel through concrete, they experience reflection, refraction, scattering, and mode conversion depending on the type, size, and orientation of the internal defects. For instance, air voids introduce a strong acoustic impedance mismatch, leading to reflection and minimal transmission. Cracks, particularly transverse ones, serve as barriers that redirect wave energy, thus prolonging the travel time and altering wave amplitude. In contrast, rust, due to its higher density and attenuative properties, primarily absorbs and scatters ultrasonic energy, but may allow partial wave transmission depending on its thickness and distribution.

This behaviour is frequency-dependent. The frequency of the ultrasonic wave determines the amount of interaction with the defect. Lower frequencies have longer wavelengths, which may bypass smaller defects, resulting in minimal changes to the signal. Higher frequencies, with shorter wavelengths, interact more aggressively with small-scale defects but are more susceptible to energy loss due to scattering and attenuation. The simulation results presented in Table 3 and Table 4 are consistent with this theoretical foundation, which highlights that mid-to-high frequencies (100–500 kHz) demonstrate enhanced sensitivity to defect presence, particularly for cracks that exhibit higher scattering behavior. This further validates the observed trend in relative error measurements and supports the selection of an optimal transducer frequency for defect detection.

To quantify the differences between the evaluated frequencies, Table 4 summarizes the percentage of maximum relative error for inhomogeneous concrete with respect to homogeneous concrete. The percentage of maximum relative error, δ, calculated using Equation (4), is needed to identify the optimal frequency corresponding to the induced vibrations of concrete. Higher relative errors indicate that the frequency is more capable of distinguishing and detecting defects in concrete.

Table 4. Percentage of maximum relative error

Frequency (kHz)	Percentage of maximum relative error (δ)		
	Concrete with air hole	Concrete with crack	Concrete with rust
20	1.27	2.76	0.69
50	1.21	6.08	0.38
100	8.96	14.50	2.14
200	14.18	45.57	13.78
500	11.32	21.70	10.94

From Table 4, the lowest frequency (20 kHz) is expected to be less sensitive to damage as it only shows a slight difference with respect to homogeneous concrete, which is only 1.27%, 2.76%, and 0.69% for concrete with air hole, crack, and rust, respectively. This is because the single wavelength of the 20 kHz ultrasonic wave in the concrete is approximately 170 mm, much greater than the size of defects included in inhomogeneous concrete samples.

For the 50 kHz frequency, there is no significant difference in concrete with an air hole (1.21%) and rust (0.38%). However, the difference is clearly recognizable in concrete with a crack, with the percentage of maximum relative error recorded being 6.08%. There is also a significant difference in the frequency of 100 kHz. While concrete with an air hole recorded the maximum relative error of 8.96% and concrete with a crack of 14.50%, concrete with rust only shows a small difference with a percentage error of 2.14%.

Both the 200 kHz and 500 kHz frequencies show clear differences for each inhomogeneous concrete case compared to the homogeneous concrete. At 200 kHz, the maximum relative error recorded for concrete with air hole, crack, and rust is 14.18%, 45.57%, and 13.78%, respectively. However, the percentage of maximum relative error for frequency 500 kHz has a slight decrement compared to frequency 200 kHz. Concrete with an air hole recorded 11.32% relative error, 21.70% for concrete with a crack, and 10.94% for concrete with rust.

A comparison between the frequencies of 200 kHz and 500 kHz, both having the highest percentage error in each case, reveals that higher-frequency transducers are more sensitive to smaller flaws due to their associated short wavelength, as opposed to low-frequency transducers with longer wavelengths. However, excessively high frequencies may lead to greater energy losses due to excessive attenuation resulting from diffuse reflections [21].

Figure 7 illustrates the percentage of maximum relative error computed for different cases and frequencies studied. Each frequency line represents a specific distance between inhomogeneous and homogeneous concrete.

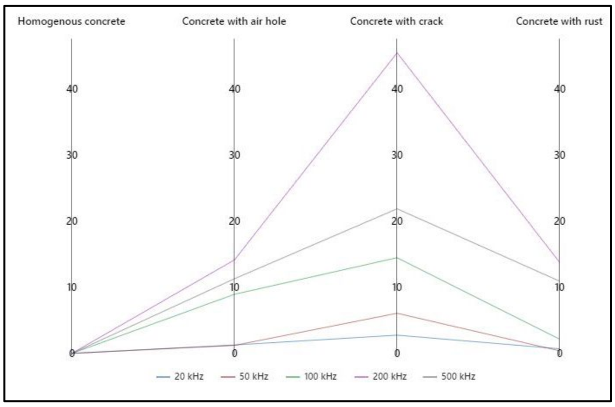

Figure 7. Percentage of maximum relative error for all evaluated frequencies.

Based on the presented results in Figure 7, 200 kHz is selected as the most suitable frequency due to its ability to distinguish individual defects in the concrete structure, compared to the 500 kHz frequency.

4. CONCLUSION

This study successfully identified the optimal frequency for ultrasonic transducers in detecting defects within concrete structures using COMSOL Multiphysics® software version 5.6. The investigation revealed that a frequency of 200 kHz could provide better distinction in detecting defects than other frequencies investigated. This frequency exhibited the highest sensitivity to defects, with notable maximum relative errors for different defect types—14.18% for air hole, 45.57% for crack, and 13.78% for rust. In contrast, lower frequencies, such as 20 kHz and 50 kHz, showed minimal sensitivity to smaller defects due to their longer wavelengths, whereas excessively high frequencies, like 500 kHz, despite being sensitive, suffered from significant attenuation and energy loss.

However, the study has its limitations. The assumption of concrete as a homogeneous material, while simplifying computations, does not fully capture the complex interactions in actual heterogeneous concrete. Future studies should consider more detailed models incorporating aggregate characteristics and explore three-dimensional simulations for more accurate results. Additionally, further research is recommended to explore the effects of varying defect sizes, shapes, and distributions to refine the detection capabilities of ultrasonic transducers.

In conclusion, this study not only highlights the critical role of frequency in ultrasonic defect detection in concrete but also provides valuable guidelines for selecting optimal transducer frequencies, thereby enhancing the reliability and effectiveness of non-destructive evaluation techniques in the industry.

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