Ultrasonic Guided Wave Measurement in a Wooden Rod using Shear Transducer Arrays

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Abstract

Research related to acoustic/ultrasonic guided wave testing in wood is still at an early stage. This paper describes the first study to perform ultrasonic guided wave measurements in a wooden rod using arrays of shear transducers. Enhancement of either longitudinal L(0,1) or torsional T(0,1) wave modes and suppression of other modes was able to be achieved using these arrays. At low frequencies, it was found that the L(0,1) wave mode had a similar speed to that obtained using the traditional resonance and time of flight methods. The torsional T(0,1) wave mode has not been used before for non-destructive testing of wood. Since it is non-dispersive, it would appear to be suitable for wood property estimation and structural health monitoring of wooden structures. These results indicate that ultrasonic guided wave testing techniques have strong potential to be used to provide improved measurement of wood properties and structural health monitoring of wooden structures.

Keywords: Wood, guided waves, ultrasonic, acoustic, dispersion curves, rod, radiata pine, aluminium, ToF, resonance.

1. Introduction

The ability to measure wood properties is important for a range of industries. In forestry, measurement of wood properties such as stiffness allows segregation and presorting to be performed before the logs are processed. This can directly increase the quality of the processed wood and result in higher profitability [1]. Structural health monitoring of wooden structures such as bridges, utility poles, and piles is also performed to detect decay [2]. There are a range of techniques that can be used to measure wood properties, such as mechanical bending tests, Near Infrared (NIR), computer tomography (CT) scans, and acoustics [3].

Acoustic testing is one of the most commonly used Non-Destructive Testing (NDT) methods as it is simple to use and is generally inexpensive compared to other approaches. Stiffness is the main wood

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property measured using acoustics. It is related to the Modulus of Elasticity, E in the longitudinal direction (direction along the grain). This is generally estimated using

$$E = \rho \, v_l^2 \tag{1}$$

where v_l is the acoustic velocity in the longitudinal direction and ρ is the density of the material. The two common methods to measure the acoustic velocity of wood is resonance and Time of Flight (ToF) [4].

The acoustic technique described above uses theory based on the assumption of 1D wave propagation in an infinitely thin, homogeneous, isotropic rod [5]. However, wood is orthotropic (speed of sound varies with direction) and a log or timber sample will have a finite diameter. For an elongated structure like a rod or log, guided waves would be expected to occur. We hypothesize that further research into guided waves in wood can lead to improved measurement of wood properties.

Guided waves are generally composed of different types of vibrations, which are referred to as wave modes. These are generally dispersive in nature. This means that different frequency components of the signal propagate at different speeds along the structure. This causes the signal to spread out as it propagates. Dispersion curves plot the variation in the speed of the wave modes with frequency. These can be represented as either phase velocity, group velocity, or wavenumber plotted as a function of frequency [6].

There have been extensive studies on guided waves in metal structures [7, 8]. Metal structures are generally isotropic and homeogeneous. In contrast, wood is highly inhomeogeneous, orthotropic, and has strong attenuation which increases with frequency. Because of this, wave propagation in wood is more complex. This might explain why there have been relatively few studies using acoustic/ultrasonic guided waves for wood.

Several studies have performed experimental measurement of guided waves in timber samples. Veres et.al [9] measured phase velocity dispersion curves for a rectangular wooden bar using a laser vibrometer and the 2D Fast Fourier Transform (FFT) method described Alleyne and Crawley [10]. Additionally, Dahmen et.al [11] utilized air-coupled capacitive transducers to experimentally measure dispersion curves for a wooden plate. The phase velocities obtained from the dispersion curves were then used to estimate the elastic constants for the wood sample. However, no previous studies have been found which have performed experimental measurement of dispersion curves for wooden circular rods, poles, or logs.

Fathi et.al also used guided waves to measure the properties of small wooden plates. They measured the velocity of the asymmetric Lamb wave mode (A0) Lamb wave by measuring the phase difference at different receiver positions [12, 13]. Machine learning techniques were used to combine measurement of A0 Lamb wave speed, moisture content, and density to predict the Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) of wood [14].

Guided waves have also been investigated for nondestructive evaluation of decay below ground level in wooden utility poles and piles. Finite Element Modelling (FEM) has been performed to investigate wave propagation in timber utility poles [15, 16]. This includes simulated dispersion curves. Holt et al. developed a technique for using a dispersive flexural wave mode generated by a hammer hit to measure the length of undecayed poles in the ground [17]. A similar method was used by Sriskantharajah et.al [18].

Subhani performed simulations which suggested that multiple transducers could be arranged around a pole to enhance reception of longitudinal and flexural wave modes [19]. Similarly, Dackermann et.al used a ring of tactile transducers which aimed to enhance the excitation of the longitudinal wave mode compared to other modes in timber utility poles [20]. Najjar and Mustapha were able to enhance the longitudinal wave mode and suppress flexural wave modes by using a ring of Micro Fiber Composites (MFC) actuators attached onto a timber utility pole both experimentally and numerically using simulations [21].

The transducers that were used in the above studies appear to have been compressional transducers. These generate and/or receive vibration mainly in a direction normal to the surface of the transducer. To the best of the authors' knowledge, the only previous study to have used shear transducers for generating/receiving guided waves in wood is that presented by Legg and Bradley [22]. In that study, the authors showed that vibrations with different speeds could be generated by aligning the shear transducers in either the torsional or longitudinal direction. It was believed that this was caused by different types of guided wave modes being generated/received. However, more work was required to confirm this.

This paper builds on the findings of [22]. Guided wave measurements were made using shear transducer on a 16 mm diameter wooden rod. Experimental dispersion curves were measured. Enhancement of specific wave modes was able to be achieved by varying the alignment of the shear transducers and using a ring array of transducers. For comparison, the same experimental measurements are repeated for an aluminium rod of similar dimensions, whose dispersion curves were known.

The work presented in this paper offers the following contributions. To the best of the authors' knowledge, it is the first work to:

(1) Experimentally measure guided wave dispersion curves for a wooden cylindrical rod.

(2) Provide a comparison between traditional resonance and ToF speed measurements in wood with the measured dispersion curves.

(3) Use a ring of shear transducers to enhance the excitation and reception of desired guided wave modes in wood while suppressing the other wave modes.

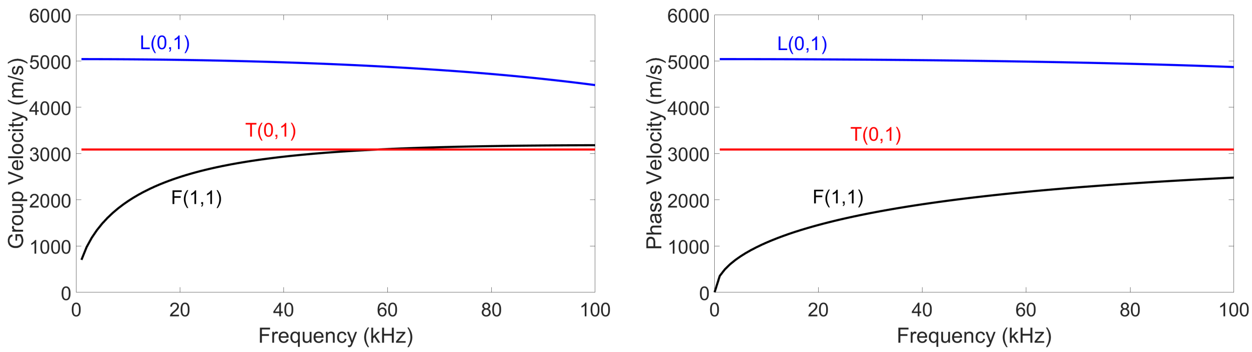
This remainder of the paper is configured as followed. Section 2 describes the methodology and samples used. The experimental results are provided in Section 3. Experimentally measured dispersion curves are shown and the effect of using a ring array of transducers are outlined. Finally the conclusion is provided in Section 4.

2. Materials and Methods

2.1. Wood and Aluminium Rod Samples

A kiln-dried radiata pine rod with a diameter of 16 mm and length of 2460 mm was used in this study. The sample was selected such that it did not contain any obvious defects or knots. For comparison purposes, a 6061-T6 aluminium rod with a diameter of 16 mm and length of 2510 mm was used.

Theoretical dispersion curves for the aluminum rod are shown in Figure 1. These were obtained using GUIGUW [23] assuming a density of 2710 kg/m^3, Young's Modulus of 68.9 GPa and Poisson's ratio of 0.33. The dispersion curves show that no higher-order wave modes exists for frequencies below 100 kHz. They also show that the flexural F(1,1) and to a lesser extent the longitudinal L(0,1) wave modes are dispersive in this frequency range whereas the torsional T(0,1) is non-dispersive.



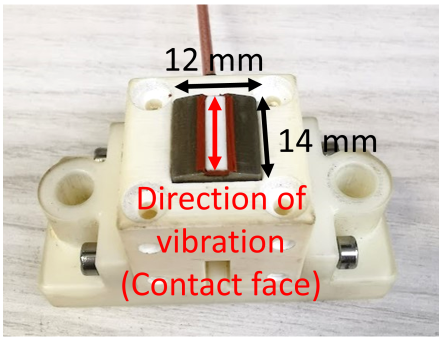
(a) (b)

Figure 1: Theoretical dispersion curves for a 16 mm aluminium rod using GUIGUW showing (a) group velocity and (b) phase velocity.

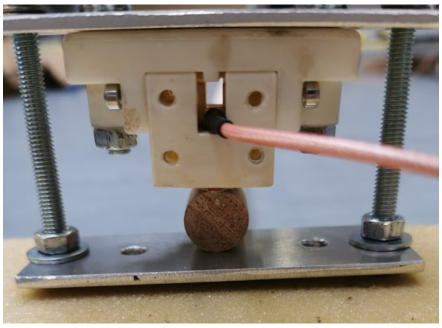
2.2. Hardware

Shear transducers from Plant Integrity Ltd (TWI) UK were used for both transmission and reception [24]. These transducers have a shear piezoelectric ceramic on their contact face which was aligned to excite/receive vibration in a direction parallel to the contact face, as shown in Figure 2(a). These are dry-coupled transducers which were pushed against the samples using springs, see Figure 2(b). For longitudinal and torsional transmission and reception, the transducers were respectively aligned either parallel or at right angles to the wood grain direction of the rod. The orientation of the transducers can be seen in Figure 3. An array of four transducers could also be mounted around the sample using the mounting system shown in Figure 4. Each transducer was pushed against the sample using springs.

An acoustic/ultrasonic signal could be generated on the samples using a hammer hit. However, more control over the signal generated was able to achieved by transmitting a signal on one or more transducers. An arbitrary signal such as a sine or chip signal was generated using MATLAB and outputted from an



(a)



(b)

Figure 2: Photo (a) shows one of the shear transducers used in the experiment. Photo (b) shows the setup used to push a single transducer against the wooden sample.

Agilent 33220A Function Generator which has a sampling rate of 20 MHz and resolution of 16 bits. The resulting signal was amplified using a custom built linear power amplifier. This could output signals with a amplitude of up to 400 Vpp. If an array of transducers were to be used for transmission, these could be wired in parallel so that the same signal was transmitted on all the transducers.

The resulting acoustic/ultrasonic signal could be measured using either a GRAS 46BF-1 microphone (for resonance tests) or using one or more transducers. The signal from each transducer was able to be amplified using a custom designed preamp circuit. The signal from each transducer was then sampled using a separate Analog to Digital Converter (ADC) channel of a Data Translation DT9832A module. A sampling rate of 2 MHz and a resolution of 16 bits were used. The sampled signal was then processed using MATLAB.

2.3. Experimental Procedure

2.3.1. ToF and Resonance Tests

Resonance and ToF speed of sound measurements were performed so that the results can be compared to guided wave measurements to determine any correlation between them. Note that the modulus of elasticity obtained using the resonance speed of sound in wood has been reported to have good correlations with

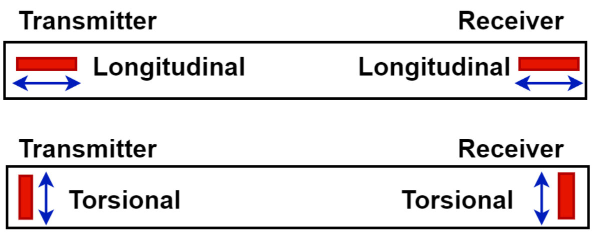
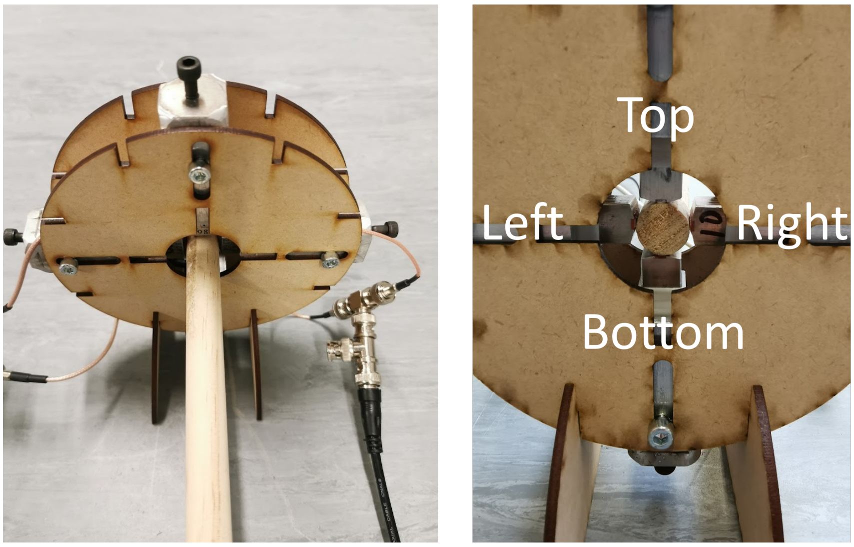


Figure 3: Diagram showing the transducer alignment in either the longitudinal or torsional direction on the rod. The red rectangle shows the contact face of the transducer and the blue arrows shows the direction of vibration.



(a) (b)

Figure 4: Photos of the transducer array mounting system used to position the transducers in a ring around the sample.

mechanical bending tests.

Measurements were obtained to calculate the resonance speed of sound for the sample. A GRAS 46BF-1 microphone was placed near one end of the sample and the opposite end was hit with a hammer. The resulting signal was sampled and resonant frequencies were obtained using the Fast Fourier Transform (FFT). The resonance speed was then calculated using

$$v_{res} = \frac{2Lf_n}{n} \tag{2}$$

where L is the length of the sample and f_n is the n^{th} resonant frequency (where $n = 1, 2, 3..$).

ToF measurements were also obtained. A transducer was positioned at each end of the sample. A hammer hit was performed at one end of the sample and the received signal from both transducers were recorded. The time T taken for the signal to first propagate between the two receiver transducers was obtained. A ToF speed was then calculated using

$$v_{tof} = \frac{\Delta d}{T}, \tag{3}$$

where Δd was the separation between the transducers. The average of 10 samples was taken as the ToF velocity.

2.3.2. Pitch Catch and Dispersion Curve Measurements

Pitch-catch measurements are often used for guided wave testing. In a pitch-catch configuration, one transducer acts as a transmitter and another transducer acts as a receiver. Pitch-catch measurements were made where the transmit and receive transducers were placed at opposite ends of the rod. A 20 kHz five cycle sine wave was used as the transmit signal and the resulting signal was saved to file. Measurements were initially made using a single transmit and a single receive transducers. This was then repeated using the transmit and receive arrays.

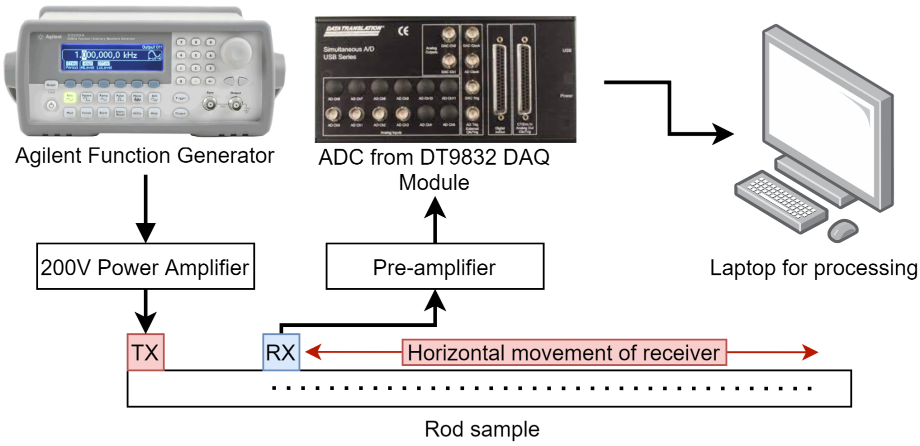


Figure 5: Experimental setup for obtaining the wavenumber plot

Guided wave dispersion curve measurements were performed using the experimental setup shown in Figure 5. A transmit transducer was attached at one end of the rod and a receiver transducer was attached 1000 mm away in a pitch-catch configuration. A chirp signal ranging from 5 to 100 kHz was transmitted on the transducer and the resulting signal was recorded. The receiver was then displaced 5 mm away from its initial position and the process was repeated for a total of 201 measurements. This experiment was repeated using the transmit and receive arrays.

Experimental dispersion curves were then obtained from this data using the method described in reference [10]. The sampled signal from all the measurement positions were formed into a $201 \times N$ matrix, where N is the number of samples. A 2D FFT was then performed on this matrix and the result was plotted. This converts the matrix from the space-time domain to the wavenumber-frequency domain. The theoretical phase velocity v_p for the aluminium rod could be overlaid on the wavenumber - angular frequency plot using the relationship

$$v_p = \frac{\omega}{k} \tag{4}$$

where ω is the angular frequency and k is the wave number. This was rearranged to give

$$k = \frac{\omega}{v_p}. \tag{5}$$

On the wave number-frequency plot, a non-dispersive wave mode will result in a straight line passing through the origin with a slope of $1/v_{ph}$. A dispersive wavemode will result in a curved line. Note that the group velocity is the rate of change of the angular frequency with respect to the wavenumber

$$v_g = \frac{\delta\omega}{\delta k}. \tag{6}$$

3. Results

3.1. Resonance and Time of Flight

Resonance and TOF measurements were made using the methodology described in Section 2.3.1. The resonance and ToF speed of sound measurements are given in Table 1. There is a good correlation between the measured average resonance and ToF velocity for wood and aluminium rods. The difference is approximately 0.6% and 2.4% respectively, which is roughly within the measurement error.

Table 1: Average resonance and ToF velocity for wood and aluminium rod samples

Material	**Resonance velocity (m/s)**	**ToF velocity (m/s)**
Wood	4456 ± 58	4428 ± 116
Aluminium	5068 ± 78	5197 ± 32

3.2. Effect of Transducer Orientation and Placement

Pitch catch measurement were performed using the method described in Section 2.3.2. The transducers were aligned in different directions to generate vibrations in the longitudinal and torsional direction respectively.

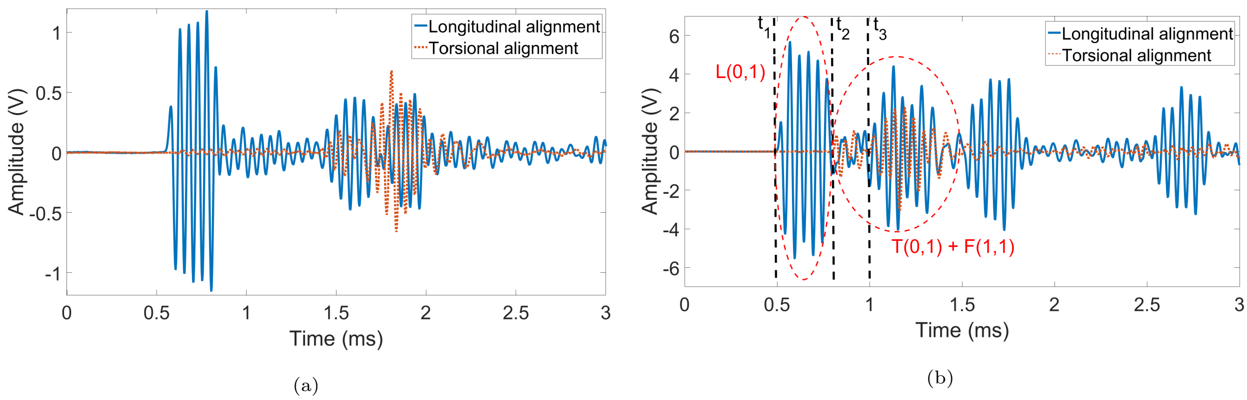


Figure 6: Plots of received signal for a 20 kHz 5 cycle sine wave excitation using different transducer orientation for (a) wood and (b) aluminium samples.

Figure 6 shows an example of the received signal for wood and aluminium using a single transmit and receive transducer. The labels t_L, t_F and t_T for the aluminium rod plot are the expected arrival times of the longitudinal, flexural, and torsional wave modes respectively. These are obtained from the dispersion curves from Figure 1(a). These plots shows that when the transducers were aligned in the torsional direction, the arrival of the received signal is slower compared to the longitudinal direction. This was observed for both wood and aluminium.

These pitch catch measurements were repeated using a single transmit transducer and four receiver transducers configured in a ring array. Figure 7 shows the normalized received signal for wood with all transducers orientated in the longitudinal and then torsional directions. It can be seen that part of the signal from the individual transducers are in phase but other parts are out of phase.

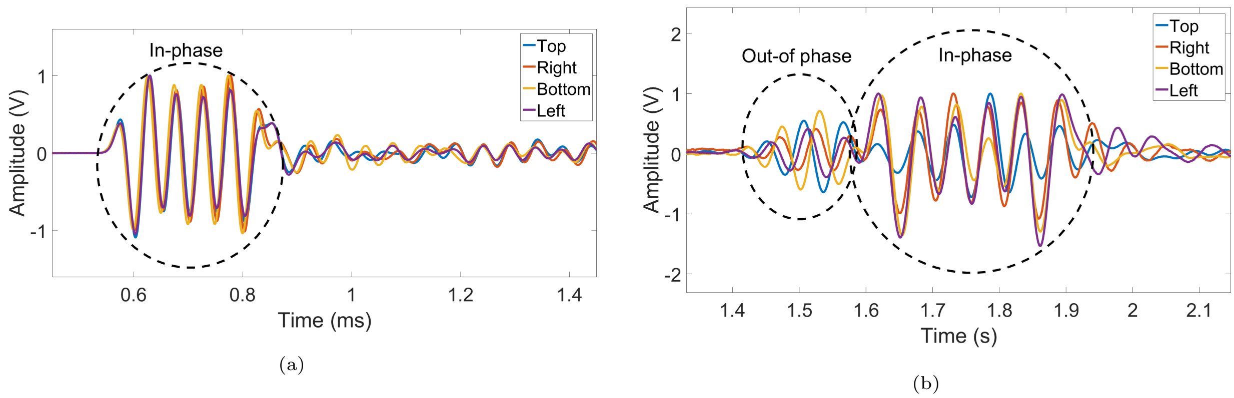


Figure 7: Plots showing the received signal for for a 20 kHz 5 cycle sine wave with four receivers attached onto different positions of the wood sample where the transducers are orientated in the (a) longitudinal and (b) torsional directions.

The measurements above were repeated for the aluminum rod. Using the theoretical dispersion curves, it was observed that the fundamental longitudinal L(0,1) and torsional T(0,1) wave modes were in phase respectively when the transducers were aligned in the longitudinal and torsional directions. However, the flexural wave mode was out of phase. This is what we would expect for a ring of transducers. By summing the signal from all four transducers, longitudinal or torsional wave modes can be enhanced depending on the orientation of the shear transducers while the out of phase flexural wave mode is suppressed. This feature has been used in guided wave testing of structures such as pipes to try to improve the accuracy of measurements by using single wave mode excitation and reception, mainly using the non-dispersive T(0,1) wave mode [25]. However, this had not been investigated before for wooden rods/poles. The results presented here show that there is strong potential for guided wave techniques, which have been developed in other industries, to be applied for improving nondestructive measurement of wood.

3.3. Measured Dispersion Curves

Experimentally measured dispersion curves were obtained using the 2D FFT method described in Section 2.3.2. Results for the aluminium rod are shown first so that we can correlate results with theory. Results for wood are then presented.

3.3.1. *Aluminium*

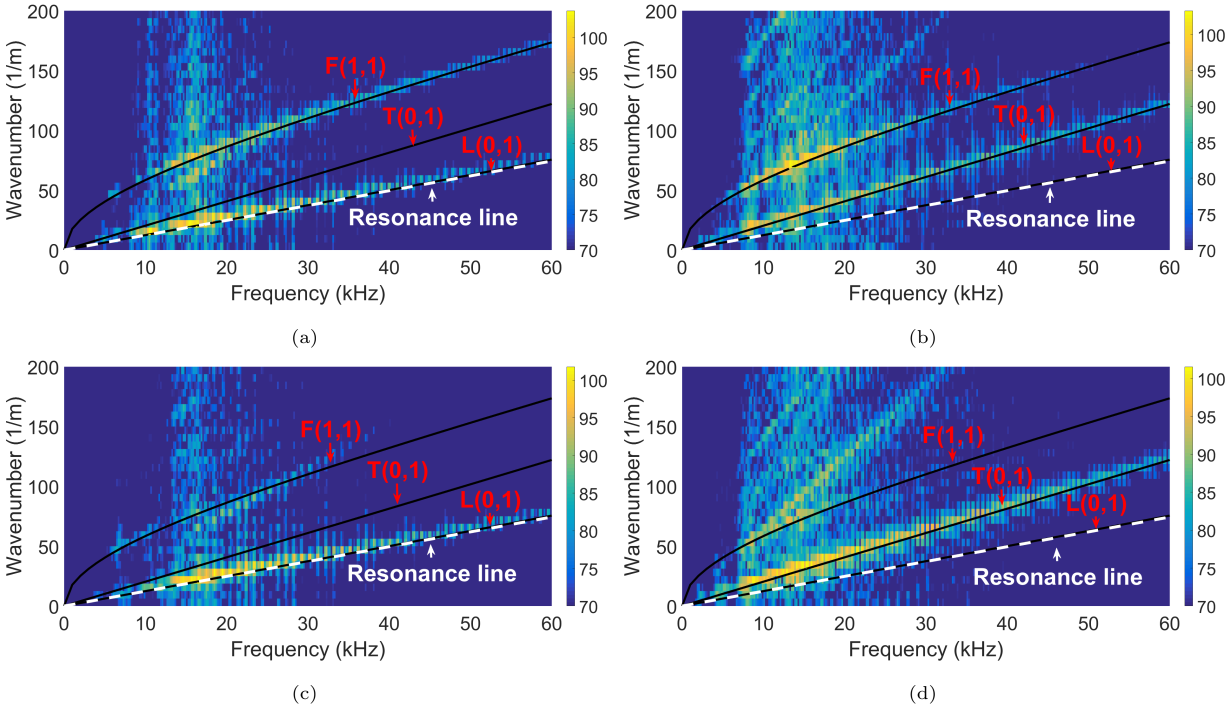


Figure 8: Wavenumber-frequency plots for the aluminium rod showing the effect of using one transmitter oriented in the (a) longitudinal direction and (b) torsional direction and four transmitters oriented in the (c) longitudinal direction and (d) torsional direction. A single receiver was used which was aligned in the same direction as the transmitter. Overlaid are theoretical dispersion curves.

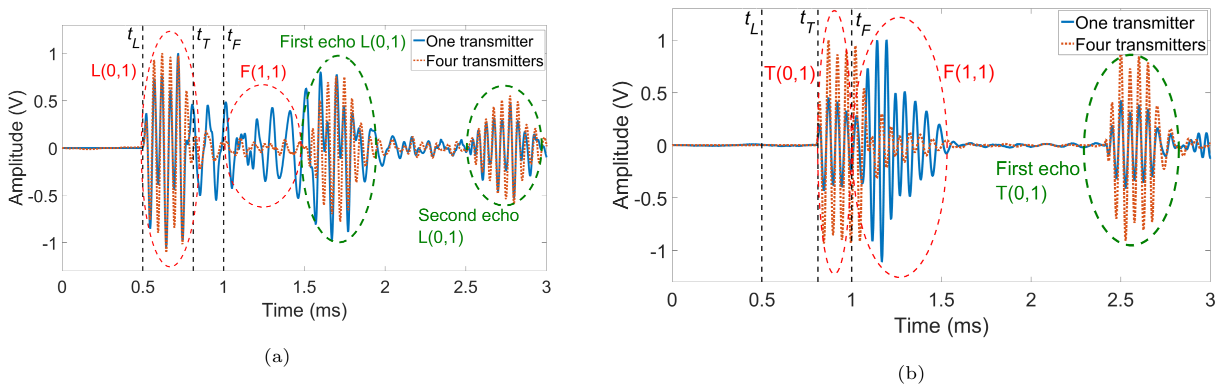


Figure 9: Amplitude normalised pitch catch received signal plots for the aluminium rod showing the effect of using one and four transmitters which are all orientated in either the longitudinal (a) or torsional (b) direction.

Figure 8 shows the experimental wavenumber-frequency plots for the aluminium sample using one and four transmitters where all transducers were either aligned in the longitudinal or torsional direction. Theoretical dispersion curves for the aluminium sample were obtained using GUIGUW and overlaid over the experimental plots. Equation 5 was used to overlay a line which corresponds to the the measured resonance speed (see Table 1). It can be seen that the resonance speed line approximately aligns with the longitudinal L(0,1) wave mode. Note that there are linear features in the wavenumber plots which do not correspond to the theoretical dispersion curves. These appear to be due to mode conversion of the signal when reflections occur. This could be mitigated by windowing the data to remove multiple echoes being processed by the 2D FFT. Using a sample with a longer length would be beneficial for this.

Figure 8(a) show that when a single transmit and a single received transducer are aligned in the longitudinal direction, two dispersion curves are observed which align with the F(1,1) and L(0,1) wave modes. However, when four transmit transducers are used with longitudinal alignment, only the L(0,1) wave mode was observed, as shown in Figure 8(c). Similarly, we can see in Figure 8(b) that using one transmit and one receive transducer aligned in the torsional direction resulted in both the T(0,1) and F(1,1) wave modes being observed. However, when four transmitters were used, the F(1,1) mode was suppressed, see Figure 8(d). This can also be seen in the time domain plots shown in Figure 9.

3.3.2. Wood

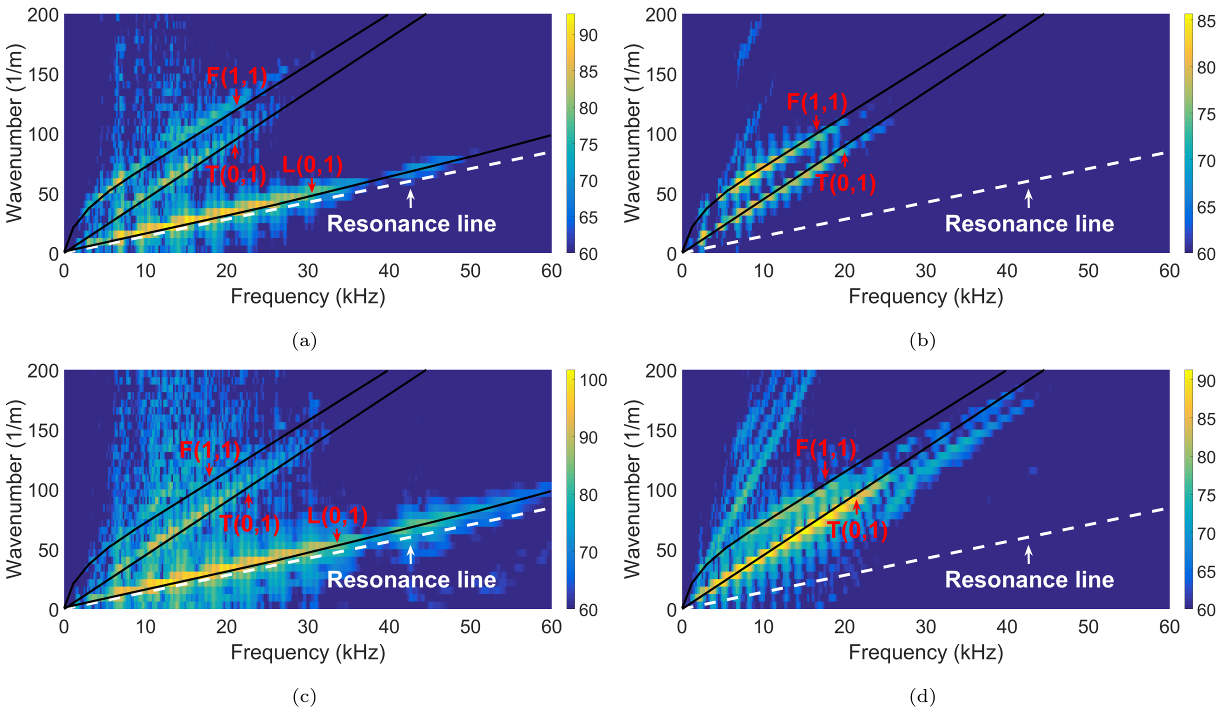
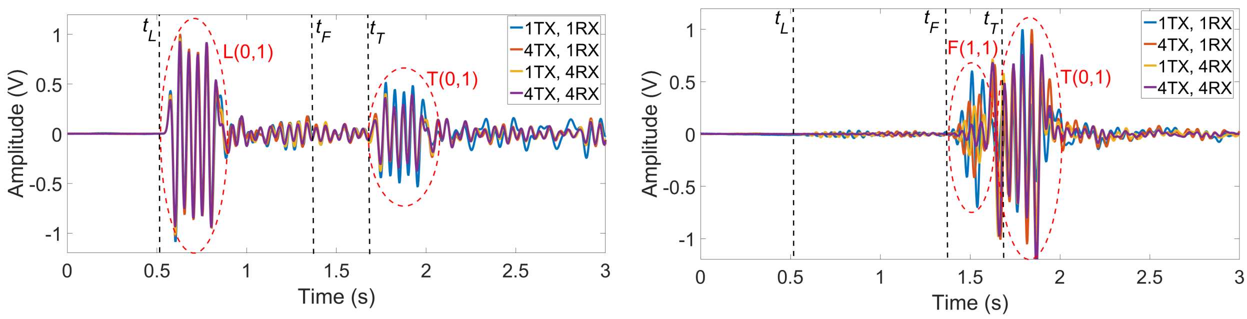


Figure 10: Wavenumber-frequency plots for the wooden rod showing the effect of using one transmitter oriented either in the (a) longitudinal direction or (b) torsional direction and four transmitters oriented in either the (c) longitudinal direction or (d) torsional direction.

Figure 10 shows the wavenumber-frequency plots obtained for the wood sample with varying alignment and number of transducers. The mechanical properties of the wooden sample were not known and hence theoretical dispersion curves were not simulated. Curves have therefore been overlaid onto the wavenumber-frequency plots to show the wave modes. Given the dimensions of the sample, three dispersion curves which represents the fundamental flexural, torsional and longitudinal modes are expected to be observed.

There are similarities between the plots obtained for the wood sample in Figure 10 and the aluminium sample in Figure 8. The resonance speed line aligns with the longitudinal wave mode at frequencies below 30 kHz. Different wave modes are excited when the transducers are aligned in the longitudinal and torsional direction. Using a ring array of four transmitters, which are aligned in either the longitudinal or torsional directions, helps to enhance the L(0,1) or T(0,1) modes and suppress other modes as seen in Figure 10(c) and (d). The use of shear transducers in a ring array can potentially be used for single mode excitation/reception in wood. This is desirable for nondestructive testing using guided waves as it enables more accurate measurements to be made.

3.4. Multiple Transducers for Transmit and Receive



(a) (b)

Figure 11: Amplitude normalised received signal plots for the wooden rod showing the effect of varying the number of transmitters and receivers orientated in the (a) longitudinal and (b) torsional directions.

The effect of using a different number of transmit and receive transducers configured in a ring array was investigated using pitch catch measurements on the wooden sample. The results are shown in Figure 11. The received signal was normalised according to the maximum amplitude of the signal. This was done so that relative comparisons can be made. The labels t_L, t_F and t_T are the expected arrival times of the longitudinal, flexural and torsional wave modes respectively and were calculated using the tangent/slope of the wave mode at the frequency of interest in the wavenumber-frequency plot in Figure 10 and converting this to group velocity using Equation 6. It can be seen from Figure 11 that the use of a ring array enable more control over the wave modes being excited and received. This is illustrated in Table 2. For example, with longitudinal alignment, the Root Mean Squared (RMS) of the torsional T(0,1) wave mode dropped from 56% to 39% relative to the L(0,1) wave mode when the transmit and receive ring arrays were used.

Table 2: Table showing the percentage (%) reduction of wave modes relative to L(0,1) when the transducers were aligned in the longitudinal direction and relative to T(0,1) when the transducers were aligned in the torsional direction for varying number of transmitters (TX) and receivers (RX).

	Longitudinal alignment		**Torsional alignment**	
	F(1,1)	**T(0,1)**	**L(0,1)**	**F(1,1)**
1TX, 1RX	9.2	56	4.6	86
4TX, 1RX	9.5	38	0.4	33
1TX, 4RX	9.3	40	3.0	26
4TX, 4RX	9.6	39	0.3	12

Similarly, for torsional alignment of the transducers, the flexural F(1,1) wave mode was reduced from 86 to 12% relative to the torsional T(0,1) wave mode when the arrays were used.

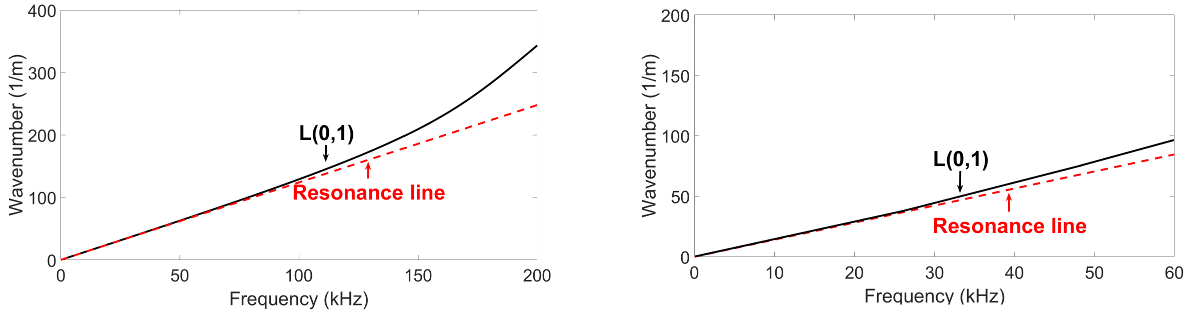
3.5. Comparison Between the Resonance Speed and Dispersion Curves

Figure 12 shows the dispersion curves for the longitudinal wave mode L(0,1) and the resonance speed line for both aluminium and wood. For aluminium, the resonance speed line aligns well with L(0,1) for frequencies below 100 kHz but starts deviating afterwards, as seen in Figure 12(a). The straight line represents the non-dispersive region of the L(0,1) whereas the curved line corresponds to the dispersive region of the wave mode. Similarly, we can see in Figure 12(b) for the wood sample. The resonance speed line aligns with L(0,1) mode but at a lower frequency (≈30 kHz) compared to aluminium.

4. Conclusion

Guided wave measurements have been performed on a 16 mm diameter wooden cylindrical rod using shear transducers. For comparison, the experiments were repeated on an aluminium rod with similar dimensions. Experimental dispersion curves were obtained using a 2D FFT method. Results showed that the amplitude of the wave modes could be controlled by orientating the shear transducers in either the longitudinal or torsional directions. Further control of the wave modes was able to be achieved using ring arrays of shear transducers. This was most noticeable for torsional alignment of the transducers where it was able to significantly suppress the flexural wave mode. It was found that the resonance speed aligns well with the speed of the longitudinal L(0,1) wave mode at low frequencies.

In future work, we plan to perform experiments on samples of different diameters to investigate the correlation between diameter of the sample with the resonance speed, ToF speed and guided wave measurements. Additionally, future work is planned to be performed to investigate the correlation between the different



(a) (b)

Figure 12: Plot of dispersion curves for longitudinal wave modes and resonance velocity for (a) aluminium and (b) wood

wave modes and mechanical properties of wood. For example, the torsional wave mode should be related to the shear modulus.

To the best of the authors' knowledge, no previous studies have been performed using the torsional wave mode for non-destructive testing of wood. The torsional wave mode is non-dispersive and hence does not spread out as it propagates. This might make it suitable for not only wood property estimation but also structural health monitoring of structures such as wooden utility poles. More research is needed into guided waves in wood to see if these can be used to provide improved measurement of wood properties and structural health monitoring of wood structures.

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