

Vibrational Characteristics of Four Wood Species Commonly Used in Wood Products

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The effects of the moisture content, density, and striking direction of a hammer on the vibrational characteristics, *i.e.*, the fundamental frequency and dynamic modulus of elasticity, of four wood species, *i.e.*, poplar (*Populus tomentosa*), mahogany (*Swietenia mahagoni*), beech (*Fagus orientalis*), and ash (*Fraxinus excelsior*), commonly used in wood products were investigated, aiming to provide basic evidence for the nondestructive testing of wood materials. The results showed that the effect of the wood species on the fundamental frequency, dynamic modulus of elasticity, and static modulus of elasticity was statistically significant. The dynamic moduli of elasticity of the four wood species were higher than the corresponding static moduli of elasticity. The effect of the striking direction on the dynamic modulus of elasticity was not significant, indicating that no matter where the hammer struck, *i.e.*, radial and tangential surfaces, the fundamental frequency was essentially constant. Negative relationships were found between the fundamental frequency and the density and moisture when the data of the four wood species were viewed as a population sample. The vibrational characteristics of each wood species varied, which can be applied to the nondestructive testing of wood.

Keywords: Wood species; Fundamental frequency; Dynamic moduli of elasticity; Striking direction

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INTRODUCTION

Non-destructive testing (NDT) techniques based on acoustics have been studied for nearly half a century in the field of wood and wood-based materials. These techniques include determining the physical and mechanical properties of wood, as well as grading, drying, and detecting defects of wood. In addition, NDT has been widely used in wood engineering and wood constructions (Kawamoto and Williams 2002; Ju *et al.* 2019; Liu *et al.* 2019; Zhao *et al.* 2019; Zhou *et al.* 2019). Commonly used NDT techniques include, but are not limited to, stress wave method, mechanical stress deformation method, vibration method, acoustic emission method, *etc.* (Lv *et al.* 2018; Xu *et al.* 2020; Fu *et al.* 2021a; Yang and Liu 2021). The scale of tested wood samples can range from non-defective small samples to full-sized wood panels (Ilic 2003; Jiang *et al.* 2008; Katalin *et al.* 2014; Turkot *et al.* 2020; Tu *et al.* 2020; Fu *et al.* 2021b; Zhang *et al.* 2021). Studies researching the relationship between the dynamic modulus of elastic (MOE_d) and the static modulus of elastic (MOE_s) have primarily used the transverse vibration method, the vertical vibration method, the ultrasonic wave method, the stress wave method, *etc.* (Mohammad and Mohsen 2017; Bi *et al.* 2020; Zhao *et al.* 2020; Fu *et al.* 2021). Previous studies showed that correlation between the MOE_d and MOE_s was relatively higher when using the transverse vibration method compared to other methods (Bi *et al.* 2020; Fu *et al.* 2021). In

addition, the MOE_d decreased as the moisture content (MC) increased when MC of wood samples were below the fiber saturation point, and the fundamental frequency showed the same trend as the MOE_d (Lu *et al.* 2016; Cai *et al.* 2020). The correlation of fundamental frequency with damping factor was negatively significant, while it was positively significant with MOE_s and acoustic conversion efficiency (Olaoye *et al.* 2020). In addition, wood density had a correlation of 0.73 and 0.50 with MOE_d and MOE_s respectively (Olaoye and Okon-Akan 2020). However, although many studies have been performed, the fundamental vibrational characteristics and their relationships are still not clear, *e.g.*, the relationships between the density and fundamental frequency and the MOE_d .

In this study, the vibrational characteristics of four wood species commonly used in wood products were studied using the transverse vibration method based on fast Fourier transform (FFT) algorithms. Specifically, the effects of the density, moisture content, and striking direction of the hammer on the MOE_d were studied and analyzed. Finally, the MOE_d and MOE_s of the four wood species were compared.

EXPERIMENTAL

Wood Materials and Equipment

Four commonly used wood species, *i.e.*, poplar (*Populus tomentosa*), mahogany (*Swietenia mahagoni*), beech (*Fagus orientalis*), and ash (*Fraxinus excelsior*), were used in this study. The commercial wood lumbers were bought from a local supplier (Nanjing, China) and stored in a conditioning room longer than 1 year. The primary testing equipment used in this study included a universal testing machine (AG-X 20kN, Shimadzu, Kyoto, Japan) and its affiliated clamps and a FFT analyzer (F9000, Ono Sokki, Yokohama, Japan) and its specially designed microphone (MI-1235, Ono Sokki, Yokohama, Japan).

Specimens Preparation

The dimensions of the full-size lumber were 3000 mm × 350 mm × 50 mm (length × width × thickness). Twelve non-defective small samples measuring 300 mm × 20 mm × 20 mm were cut for each wood species according to GB/T standard 1936.2 (2009). For the ash and beech wood samples, grains in the transverse section were clear and straight, but it was difficult to distinguish the wood grains for the other two wood species.

Testing Methods

Figure 1 shows the setup for measuring the vibrational characteristics of the four wood species using the transverse vibration method based on FFT algorithms. The sample was hung on a wood framework *via* rubber bands, and the two hanging points were 0.224 times the sample length away from the two ends of the sample according to GB/T standard 1936.2 (2009) and ASTM standard D6874 (2020). The microphone used to receive signals was fixed upon the sample at a distance in mm. The settings of the FFT analyzer were as follows: a sample frequency of 0 to 4 kHz, a sample point of 2018, and the threshold of microphone was 1 Pa to filter environmental noise. The testing method involved striking the right end of the sample with a professional hammer at a point 20 mm away from the right end and the signals were received by the microphone at the other side. One must be trained before formal testing can occur in order to keep the hammer force large enough to trigger the threshold. Five replications were repeated for each sample, and 12 samples were prepared for each wood species. In addition, the ash and beech wood samples were struck

at both their radial and tangential surfaces. The dynamic modulus of elasticity (MOE_d) was calculated by Eq. 1,

$$E_d = 0.9464l^4pf^2/h^2 \quad (1)$$

where E_d is the dynamic modulus of elasticity (N/mm^2), l is the length of the sample (mm), p is air dry density (g/cm^3), f is the fundamental frequency (Hz), and h is the height of the sample (mm) (Tao *et al.* 2019). After the transverse vibration tests, the samples were reused to conduct a three-point bending test to calculate the static modulus of elasticity (according to ISO standard 16978 (2003)), and the modulus of rupture (MOR) (according to GB/T standard 1936.1 (2009)). The loading rate of the testing machine was 5 mm/min, and the MOE_s was calculated according to Eq. 2,

$$E_s = \Delta Pl^3/(4\Delta fbh^2) \quad (2)$$

where E_s is the static modulus of elasticity (N/mm^2), ΔP is the change of load in elastic stage of three-point bending test (N), Δf is the deflection corresponding to ΔP (mm), and b is the width of the sample (mm); the MOR was calculated according to Eq. 3,

$$\sigma = 3P_{max}l/2bh^2 \quad (3)$$

where σ is the modulus of rupture (MPa) and P_{max} is the maximum bending capacity (N).

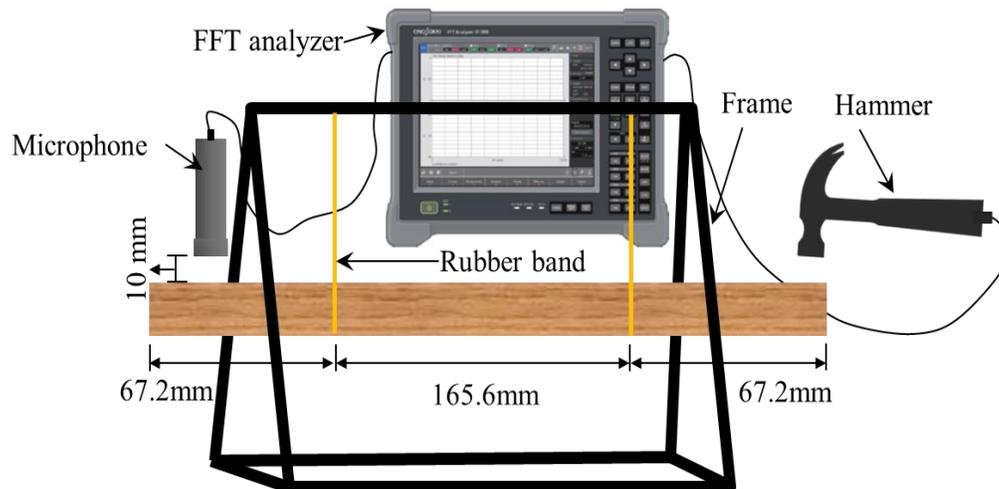


Fig. 1. The setup for measuring the vibrational characteristics of wood

Non-defective small samples (measuring 20 mm × 20 mm × 20 mm) were cut from the ends of tested samples in order to measure the density, air dried density, moisture content (MC), volume shrinkage coefficient (K), and density at 12% MC ($p_{12\%}$), according to GB/T standard 1931 (2009) and GB/T standard 1933 (2009). The K and $p_{12\%}$ were calculated according to Eqs. 4 and 5, respectively,

$$K = (V_w - V_0)/(V_0 \times W) \times 100\% \quad (4)$$

$$p_{12\%} = p_w[(1 - 0.01(1 - K)(W - 12\%)] \quad (5)$$

where K is the volume shrinkage coefficient (%), V_w is the volume of the sample at air dry conditions (cm^3), V_0 is the volume of the sample at oven dry conditions (cm^3), W is moisture content in air dry condition, $p_{12\%}$ is the density of the sample at a moisture content of 12% (g/cm^3), and p_w is the density of the sample at air dry conditions (g/cm^3).

Statistical Analysis

The effect of the wood species on the fundamental frequency (F_1), MOE_d, and MOE_s was analyzed using analysis of variation (ANOVA) with a general linear model. Mean comparisons were conducted using the least significant difference (LSD) method if significance existed between the four wood species. The above statistical analysis methods were conducted using SPSS v22.0 (IBM, Armonk, NY) at a 5% significance level.

RESULTS AND DISCUSSION

Density and Moisture Content of the Evaluated Wood Species

Table 1 shows that the air-dry density and MC of the four wood species were significantly different. The order of the air-dry density and MC from high to low is as follows: ash, beech, mahogany, and poplar. In addition, the MCs of the beech and mahogany samples were not significantly different. Since density is dependent on the MC, Eqs. 2 and 3 were adopted to transfer the densities of all wood species to the same MC, *i.e.*, $p_{12\%}$. Table 2 shows that the order of $p_{12\%}$ from high to low is as follows: ash, beech, mahogany, and poplar. This was convenient for further comparing the vibrational characteristics of the four wood species.

Table 1. Mean Comparisons of the Density and Moisture Content of the Evaluated Wood Species

Wood Species	Air-dry Density (g/cm ³)	MC (%)	Volume shrinkage Coefficient (%)	Density at a MC of 12% (g/cm ³)
Poplar	0.45 (9.23) D	8.64 (2.52) C	39.62	0.46
Mahogany	0.65 (5.75) C	9.26 (2.20) B	33.55	0.66
Ash	0.74 (2.54) A	9.69 (2.37) A	54.28	0.75
Beech	0.68 (5.53) B	9.22 (2.70) B	0.460	0.69

Note: the values in parenthesis are the coefficient of variance (COV) as a percentage; the mean value in the same column not followed by a common upper letter is significantly difference at the 5% significance level.

Vibrational Characteristics

Table 2 shows the typical outputted results *via* FFT. Figure 2a is the hammer force and time curve, Fig. 2b is the frequency response spectrum, as well as the ratio of acoustic pressure to hammer force, and Fig. 2c shows an acoustic attenuation curve, which is in accord with the exponential function. In addition, Fig. 2d gives the coherence of the hammer force and acoustic pressure. The fundamental frequency (F_1) can be obtained using the following methods: pick the frequency corresponding to the peak value shown in Fig. 2b, and then check Fig. 2c. If the coherence is close to 1, then this frequency is the F_1 .

Figure 3 shows the typical load and deflection curves of the four evaluated wood species, which indicated that the failure mode of mahogany was brittle fracture, while the other species were ductile fracture. The MOE_s and MOR can be obtained using Eqs. 2 and 3, respectively, and the lower and upper load limits were 300 N and 700 N, respectively, so the ΔP was 400 N.

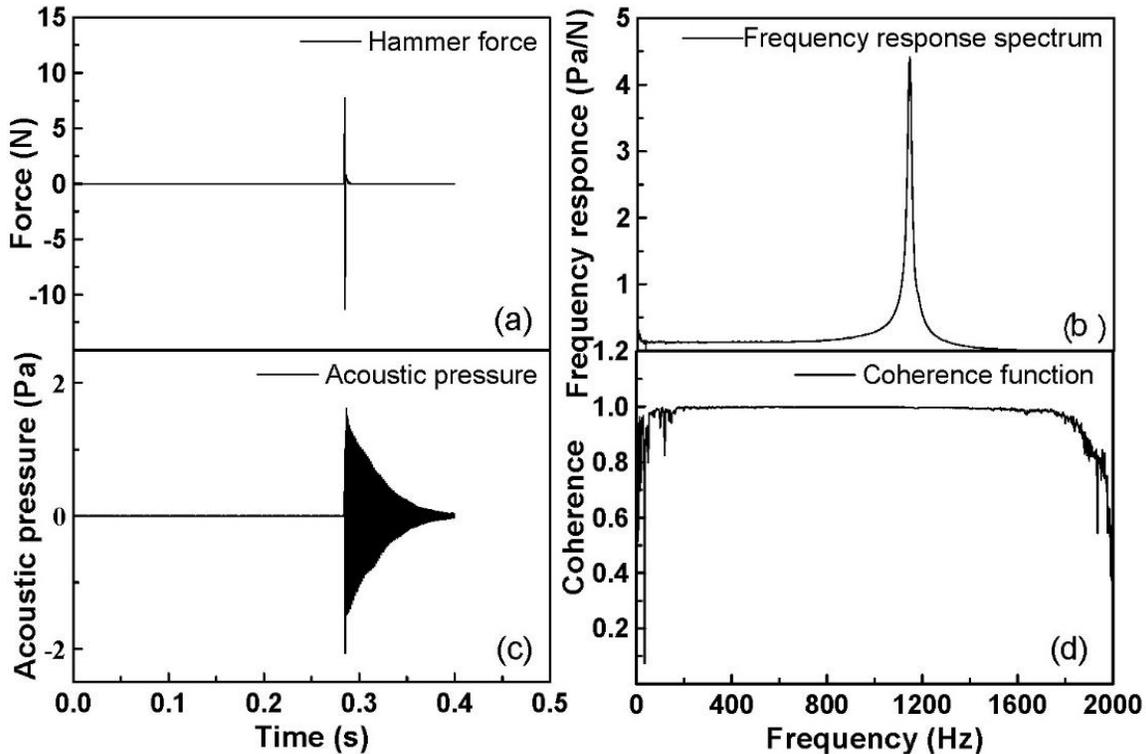


Fig. 2. Data output *via* FFT: (a) the hammer force; (b) the frequency response spectrum; (c) the acoustic pressure; and (d) the coherence between the hammer force and acoustic pressure

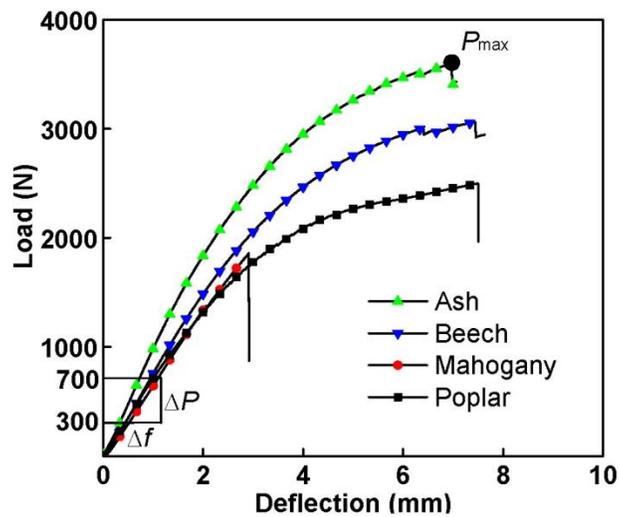


Fig. 3. Typical load-deflection curves under three-point bending

Table 2 shows the fundamental frequency, MOE_d , MOE_s , and MOR of the four evaluated wood species. The wood species had a significant effect on the MOE_d and MOE_s , but the difference in these values for ash and beech was not significant. The effect of the striking direction on the MOE_d of ash and beech wood was not significant. The MOE_d values of all wood species were greater than their corresponding MOE_s values (Yin *et al.* 2005; Jiang *et al.* 2008; Fu *et al.* 2021). For the MOR values of all evaluated wood species, the order from high to low was as follows: ash, beech, poplar, and mahogany.

Table 2. Summaries of the Vibrational and Mechanical Properties of the Four Evaluated Wood Species

Wood Species	Direction	F_1 (Hz)	MOE _d (MPa)	MOEs (MPa)	MOR (MPa)
Poplar	n/a	1147 (5.0)	11175 (9.6) B	7118 (13) B	82.5 (14.2)
Mahogany	n/a	838 (6.0)	8598 (12) C	6399 (15.8) C	59 (20.7)
Ash	R	1026 (2.3)	15789 (6.5) A	11192 (11.5) A	120.4 (11.9)
	L	1048 (2.4)	15652 (5.6) A		
Beech	R	990 (8.4)	15204 (20) A	10958 (16) A	116.3 (12.6)
	L	1047 (7.3)	14444 (16) A		

Note: R and L denote the radial and tangential surface of the wood sample, respectively; Values in parenthesis are the coefficient of variance (COV) as a percentage; the mean value in the same column not followed by a common upper letter is significantly difference at the 5% significance level.

Concerning the above results, attention must be paid to the fact that the MOE_d of poplar was greater than the MOE_d of mahogany, but the density of mahogany was greater than the density poplar. According to Eq. 1, the MOE_d is positively proportional to the F_1 and density when the dimension of the sample is constant. Although the density of poplar was significantly less than the density of mahogany, the F_1 of poplar was significantly greater than the F_1 of mahogany. Therefore, further analysis is needed to determine the relationship between the density and the F_1 .

Figure 4 shows the relationships between the F_1 and MC and the density. A previous study (Liu *et al.* 2005) reported a general method for applying FFT to measure the MOE_d of various wood species, so all wood species can be regarded as a population sample with different densities and MCs. The fitting line and correlation coefficients showed that there were negative relationships between the F_1 and MC, and previous studies also confirmed this point (Lu *et al.* 2016; Cai *et al.* 2020). The F_1 decreased with the increase of wood density, even though these correlation coefficients were relatively lower, which resulted from the deviation of mahogany data from the population samples.

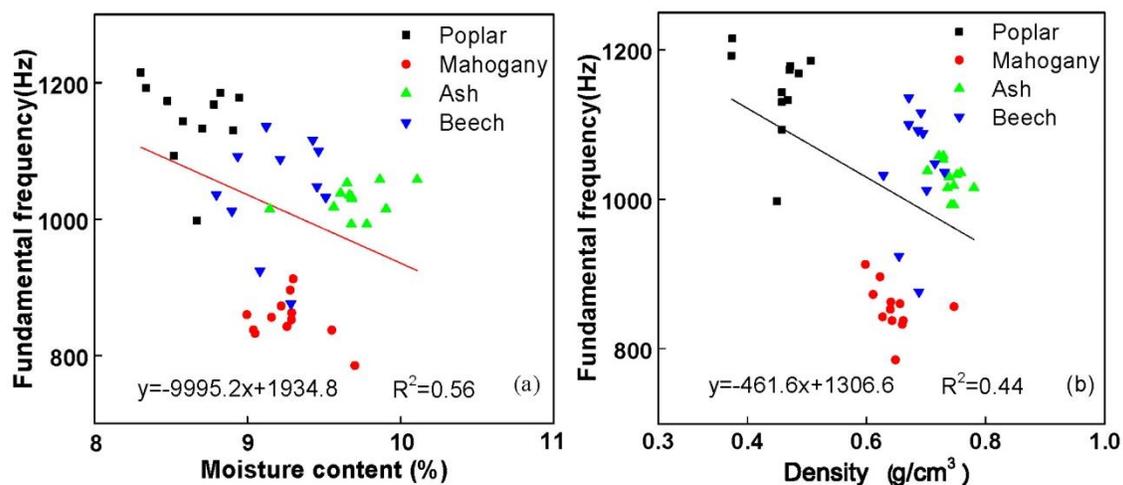
**Fig. 4.** Relationships between the fundamental frequency and the (a) moisture; and (b) density

Figure 5 shows the correlations between the F_1 and MC and the density using a color map. A rainbow band was generated with changes in the MC and density, apart from

the region corresponding to mahogany circled in red. Figure 5 also shows that the F_1 decreased as the MC increased when density was a constant. However, when the MC was controlled, the F_1 decreased in a wave trend as the density increased. These trends also confirmed the results shown in Fig. 4.

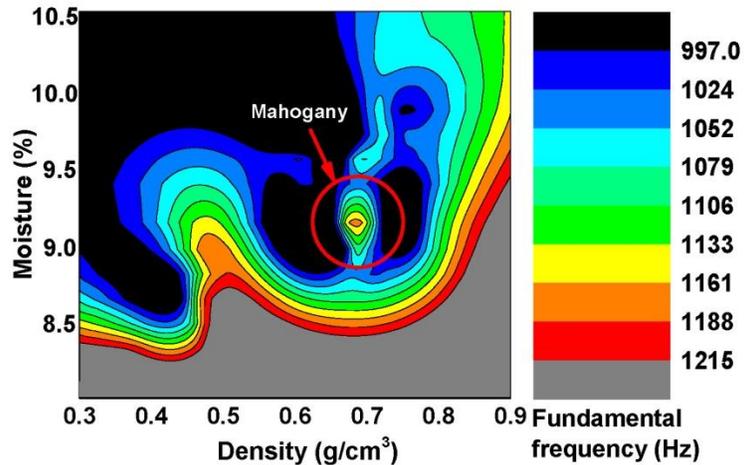


Fig. 5. Color map showing the relationship between the fundamental frequency and density and the moisture

These results suggest a deviation of the results for mahogany, relative to those of the other species. This may be due to the interlocking grain of mahogany in the longitudinal direction (Bergman *et al.* 2010). The other grains of the evaluated wood species in the longitudinal direction were straight (Fig. 6). In addition, this may be the reason why mahogany exhibited brittle fractures whereas the other species had ductile fractures. Figure 7 shows that the acoustic pressure attenuation curve of mahogany was remarkably different from the other three wood species. Specifically, the acoustic pressure attenuation curves of ash, beech and poplar decreased exponentially as time increased, while the acoustic pressure attenuation of mahogany decreased in a wave trend. This phenomenon may be used to judge the grain trend in the longitudinal direction of wood and provide new evidence for wood grading based on NDT.

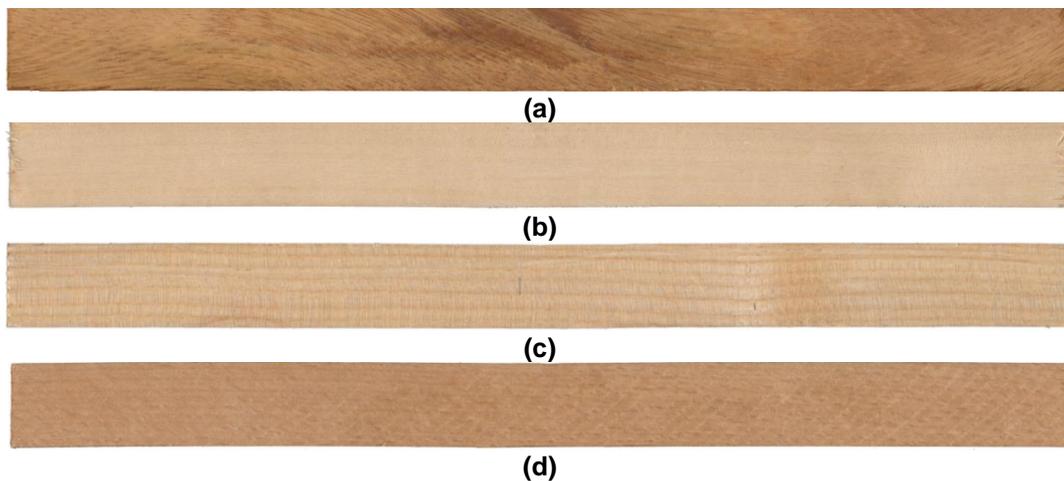


Fig. 6. Longitudinal grains of the wood samples: (a) mahogany; (b) poplar; (c) ash; and (d) beech

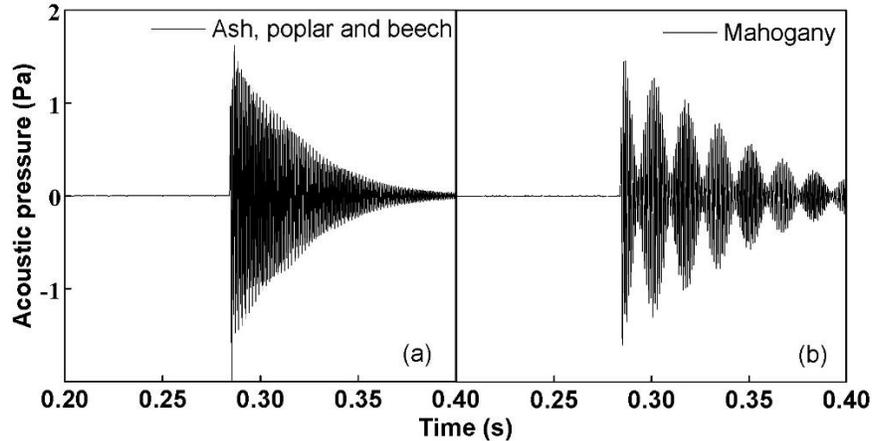


Fig. 7. Acoustic pressure attenuation curve of the evaluated wood species evaluated

In addition, the aim of this paper was to compare the vibrational characteristics of four wood species in air-dry condition or equilibration moisture content, so the moisture content was not adjusted. All above results shows that wood moisture content and wood density have interactive effects on wood fundamental frequency and MOE_d . Wood moisture content and density also are the basic wood physical parameters which directly relate to the wood mechanical properties (Yin and Liu 2021). However, wood moisture content and density varies from one wood species to another one, even though in the same condition (Fu *et al.* 2021b; Yin and Liu 2021). Thus, finding another indicator to reflect the mechanical properties of wood is important. The results of this study showed that vibrational characteristics could be an effective alternative. In future work, the effects of actively controlling moisture content and density on vibration characteristics of different wood species will be studied.

CONCLUSIONS

The vibrational characteristics of four commonly used wood species in wood products were studied *via* the transverse vibration method. The following conclusions were drawn:

1. The effect of the wood species on the fundamental frequency (F_1) and the dynamic modulus of elasticity (MOE_d) were significant. Specifically, the order of these values, from high to low, was as follows: ash, beech, poplar, and mahogany. However, the difference between ash and beech was not significant.
2. The striking direction of the hammer had no significant effect on the MOE_d ; specifically, it did not matter if the radial or tangential surface was struck, the MOE_d was always almost constant.
3. There were negative relationships between the F_1 and moisture content and the density when all wood species evaluated were regarded as a population sample.
4. The mechanical and acoustic behaviors of mahogany were remarkably different from the mechanical and acoustic behaviors of the other three evaluated wood species, which was likely due to its interlock grain in the longitudinal direction.

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