MODAL FREQUENCIES TO ESTIMATE THE DEFECT POSITION IN A FLEXURAL WOODEN BEAM

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An inexpensive methodology is proposed to identify and locate a single defect within a wooden beam using free flexural vibration technique. A similar approach has been introduced in the literature based on free longitudinal vibration, which was selected to be a leading frontier for the present research. The flexural vibration technique was tested for five groups of the absolutely clear specimens while holding a manually drilled hole at 0.1, 0.2, 0.3, 0.4, and 0.5 of their total span. The beams were tested in free flexural vibration with both ends in a free condition before and after drilling, and relative shifts of modal frequencies due to the presence of the defects were measured and compared to their mathematically calculated values in a sinusoidal equation. Using the method of least squares, a coincidence factor was developed based on the differences of the measured and calculated shifts of the four initial resonance frequencies where the minimum district of the coincidence factor curves successfully indicated the defected area. Though the longitudinal vibration approach was promising enough to estimate the position of the defect, its combination with the flexural vibration might increase the degree of confidence in the identifications.

Keywords: Defect; Drilled hole; Least square; Vibration; Wood

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INTRODUCTION

Wood, a naturally derived engineering material, is commonly used in buildings, furniture, timber bridges, and many other applications. The clarity and soundness of the structural members might be essential to guarantee the suitability of their performances, while natural or artificial defects in woodcrafts would reduce the strength and eliminate their efficiencies in final engineering products. Natural growth defects such as knots, compression wood, and oblique fiber orientation (Thelandersson 2003) in addition to the possibility of external damage, such as termite attacks and pockets of rot, as well as mechanical degradation due to overload and fatigue, weaken its structural capacity and shorten the service life span (Choi et al 2007). Identifying defects and their positions in structural members have been considered as the most important concern in this area. X-ray digital scanning is the perhaps the most accurate technique for identifying such defects (Oja et al. 2010; Skog & Oja 2009; Pietikäinen 1996; Grundberg and Grönlund 1997; Wang et al. 1997; Burian 2006), but there are difficulties in transporting and maintaining such equipment, which tends to be expensive in comparison with timbers that are the object of the quality control. If there were an inexpensive rival, it might be hard to justify some current applications of the X-ray method. Developing new and inexpensive methodologies comparable to the prices of this renewable engineering material has been very desirable for engineers in two last decades. Among these methods, acoustic measurements have become common in wood testing. Such measurements as sonic velocity, frequency, amplitude, damping, and the traveling time of sound in wood can be used to test standing trees (Sandoz and Lorin 1994; Betge and Mattheck 1998), lumber (Matthews 1994; Ross 1996; Sandoz 1996), built-in materials (Divos 1998), beams in wooden bridges (Emerson 1998), and panels (Kruse et al 1996).

Practically, the defects are estimated in timbers by stress wave traveling time and amplitude (Divos et al. 2001). Modal analysis is also applied to determine and localize defects in wood by the shape of the flexural vibration waves (Yang et al. 2002). Based on studies by Yang et al., it was suggested to detect the presence of defects and to determine their location in wood. Accordingly, the effects of cracks and holes as artificial defects on the dynamic responses of the timbers to the flexural excitations were properly investigated (Roohnia et al 2010, 2011a), which eventually led to possible recognition of the absolutely sound specimens among a community of visually graded and selected timbers. This method of assessment even was able to meet the meticulous criteria in the woodcraft musical instrument industry (Roohnia et al 2011b,c). Occasionally, the flexural excitations, the longitudinal, or the combination of both dynamic tests have been used to assess wood (Sobue et al 2010; Roohnia et al 2011d). The instrumentation costs for such vibrational tests, which are approximately the price of a personal pocket or laptop computer, have encouraged the recent valuable advancements in low cost and rapid nondestructive technologies.

Research has shown that defects affect the strength of a structural timber such as a knot inducing a resonance frequency shift of vibration (Nakayama 1974; Sobue and Nakano 2001; Brancheriau et al 2006). Similarly, several proposals aiming at the identification of a local defect might be those such as the flexural curve of a beam in a static bending test (Nagai et al 2007) and the flexural curve associated with a transfer function in flexural vibration (Yang et al 2002; Choi et al 2007). One outstanding methodology here was proposed by Sobue et al. (2010). In that study, an inverse solution procedure enabling the identification of the defect position in a beam, which was made possible by the resonance frequency of longitudinal vibrations, was exploited. Accordingly, resonance frequency shifts of a power spectrum due to defects in a longitudinally vibrating beam when both ends were free were investigated by both numerical and experimental analysis. The frequency shift could be approximated by a sinusoidal curve. Calculation results agreed well with those of the experiments in which artificial round holes were drilled as the defect model. Experimental equations predicting the amount of the frequency shift as a function of the defect position were obtained. In the inverse procedure, the defect position was so determined by comparing the resonance frequencies between the experimental and estimated power spectra at which the developed coincidence factor became a minimum. The results determined high validity of the proposed method to identify the defect position of a single predominant defect. The proposed methodology by Sobue et al. (2010) inspired the current researchers to re-evaluate the validity for flexural vibration tests. Though the coincidence factor in longitudinal vibration was promising enough to estimate the position of the defects, its combination with flexural vibration might increase the degree of confidence in identifications. Meanwhile, in relatively shorter beams, the second and third beams to upper longitudinal modal frequencies would become blind or very difficult to be identified with conventional inexpensive receivers such as a microphone, while several modal frequencies might be easily obtained in flexural vibrations where the frequencies are considerably smaller. Whereas flexural vibrations can be poorly informed by one resonance frequency to identify the defects position, the flexural vibrations might be tried here to overcome the limitations of longitudinal modal frequencies.

EXPERIMENTAL

To follow up on the preliminary investigations on the effects of drilling on the dynamic response of the wooden beams as conducted by the present research team (Roohnia et al 2011c), an oriental beech (*Fagus orientalis*) timber was collected from two commercial logs. Following ISO 3129 International Standards (1975), 100 rectangular, visually clear and sound wooden bars were randomly obtained from all parts. The specimens cut to their final nominal dimensions of 2×2×36 cm R×T×L were kept in a conditioning chamber at 21^{o}C and 65% relative humidity for 2 weeks until their moisture content was stabilized. The specimens were sorted out based on severe and accurate clarity criteria in accordance with the Timoshenko bending theory correlation coefficient (Brancheriau and Bailleres 2002; Roohnia et al. 2010) and relative differences between dynamic longitudinal modulus of elasticity out of radial and tangential flexural vibrations (Roohnia et al. 2011c). The best 37 specimens were selected and randomly divided into five groups of seven to apply drilling to the tangential surface with a diameter of 10 millimeters distributed in the radial direction (Fig. 1) at different relative distances from an end of different samples. As indicated in Table 1, to simulate the local defects in wood, two specimens were kept in a climatic chamber for a final efficiency test. Four initial modal frequencies were obtained in fast Fourier transform spectrum both in LR and LT free flexural vibration in free-free beams following the methodology and devices described in previous literature (Roohnia 2010, 2011c) before and after drilling the holes. Despite the ratios for upper modal frequencies to the first mode of flexural vibration ($r_n=f_{n,0}/f_{1,0}$) being known for the isotropic materials, it was rebuilt for the clear orthotropic specimens in the present study before applying the drilling holes based on the averages of all 35 repetitions.

Identification of the defect position from the power spectrum of the flexural vibration was performed based on the method of least squares and transfer matrix method (Sobue et al. 2010). The defect position x was so determined that the differences of the resonance frequencies between the experimental and estimated spectra became minimal. The following coincidence factor, $S(x)$, was used as the identification parameter. A relative shift of frequency in an arbitrary vibration mode, rsf_n, due to a defect was given by,

$$rsf_n = \frac{f_n - f_{n,0}}{f_{n,0}} \times 100 = \frac{f_n - r_n \cdot f_{1,0}}{r_n \cdot f_{1,0}} \times 100 \tag{1}$$

where f_n is an experimental resonance frequency in an n^{th} mode of a specimen with a defect, and $f_{n,0}$ and $f_{1,0}$ are resonance frequencies of an n^{th} and the fundamental modes in a defect-free condition, respectively. For testing the validity of Eq. 1, the equality of the parameters, $f_{n,0}$ and $r_n.f_{1,0}$ were examined in separate modes of vibration. Using the magnitude of the maximum frequency shifts in separate modes of vibration, the frequency shifts, k_n, at an arbitral defect position x was approximated by a sinusoidal curve,

$$k_n(x) = \frac{a_n}{2}\left[\cos(2n\pi x) - 1\right] \tag{2}$$

where a_n is a maximum amplitude of the frequency shift and n represents the vibration mode number.

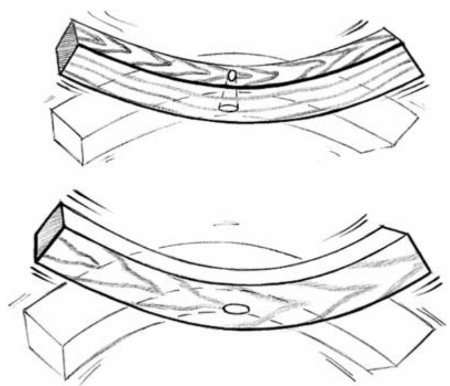


Fig. 1. A beam carrying a drilled hole under flexural vibrations in LR (top) and LT (bottom) directions

Table 1. Drilling Scenarios for 5 Groups of Clear and Sound Beams

Group	Replications	Hole diameter mm	Relative distance of drilling from an end
1	7	10	0.1L
2	7	10	0.2L
3	7	10	0.3L
4	7	10	0.4L
5	7	10	0.5L

*L is total free span of the beam

The number of field matrices of the beam was simulated to be 100 without any consideration of the nominal drilling diameter in the following experiment. In other words, a defect could be placed and identified anywhere. Sobue et al. (2010) showed that the value x giving the minimum value of $S(x)$ in Eq. 3 or the coincidence factor is the optimal solution for identifying the defect position,

$$S(x) = \left[rsf_1 - k_1(x)\right]^2 + \left[rsf_2 - k_2(x)\right]^2 + \left[rsf_3 - k_3(x)\right]^2 + ... + \left[rsf_N - k_N(x)\right]^2 \qquad (3)$$

where N is 4, the highest vibration mode in the current study. Finally, the coincidence approach was tested with the two remaining additional clear specimens that were drilled at the 0.15 and 0.45 relative distances from an end, with unknown modal frequencies under defect-free conditions.

RESULTS AND DISCUSSION

The ratios of the upper modal frequencies to the fundamental mode of flexural vibration $(r_n = f_{n,0}/f_1)$ for the isotropic materials and the clear orthotropic wooden specimens under the study (rebuilt values) before applying the drilling holes based on the averages of the total of 35 replications are indicated in Table 2.

Table 2. The Ratios of the Upper Modal Frequencies ($f_{n,0}$) to the Fundamental Mode ($f_{1,0}$) of Flexural Vibration for the Isotropic Materials and Absolutely Clear Wooden Specimens

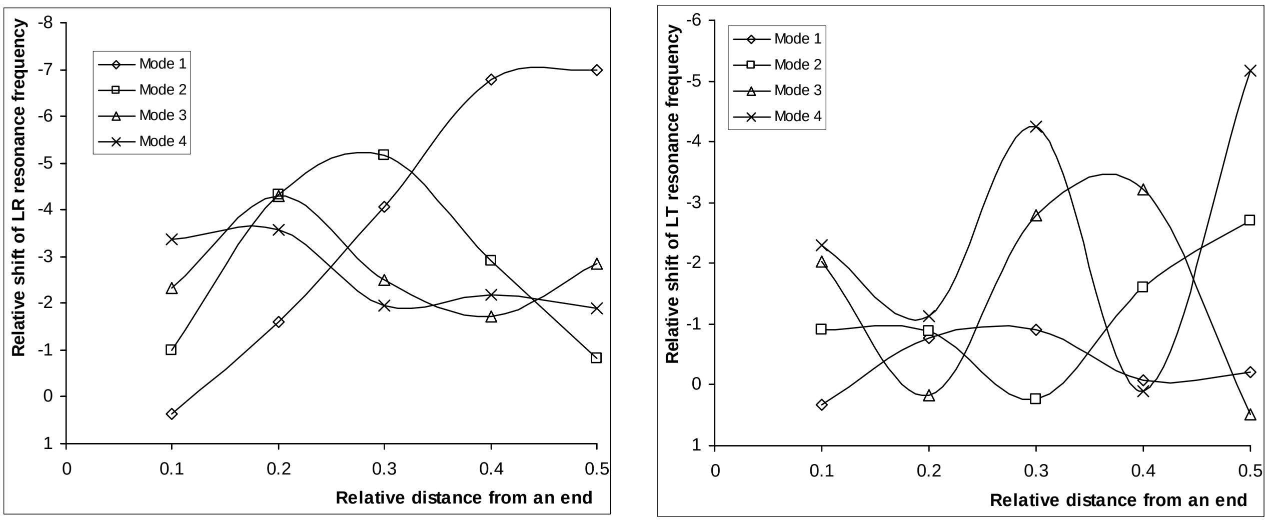
Mode	$r_n = f_{n,0} / f_{1,0}$	
	Isotropic Materials	Sound wooden specimens*
1	1	1
2	2.756	2.614
3	5.404	4.761
4	8.933	7.231

*Based on the averages of 35 replications

The differences of r_n for the isotropic materials and the specimens under the study might be a result of the relatively anisotropic behavior of the wood as a marginally accepted orthotropic material or the effects of shear deflection and rotary motions of modal frequencies due to the L/t ratio, which was not a concern in this partial elementary research; however, the rebuilt r_n values, which were applicable to the specimens under the study, were used in Eq. 1.

The measured relative shifts of frequencies in the four initial modes of LR and LT flexural vibrations were evaluated using Eq. 1 and plotted against the relative distances of drillings from an end in Figs. 2a and 2b. In both cases, the curves seemed to start from the zero point followed by a sinusoidal relation. Applying the sinusoidal Eq. 2, the relative shift of frequencies was manually calculated, where the correlations and equality of the measured and calculated values were tested in Figs. 3a and 3b.

The coefficient of determination, R^2, in the case of LR flexural vibration was relatively high, and the magnitude of the calculation value was approximately equal to the experimental value. This might be interpreted as an advantage of choosing the maximum amplitudes separately for individual modes of flexural vibration comparable to the single maximum amplitude applied for the longitudinal vibration technique, by Sobue et al. (2010). So, the approximated sinusoidal curves could successfully be provided in the transfer matrix method as shown in Fig. 4 for LR flexural vibration. The calculated sinusoidal equation and any other similar approximations could not be fitted to the frequency responses of LT flexural vibration (Fig. 3b) that might be the result of the orientations in the holes. Based on the findings in Roohnia et al. (2011c), the dynamic response changes of the similarly defined drilled beams in LT flexural vibration was not significantly identifiable.



A B

Fig. 2. Measured relative shift of LR (a) and LT (b) modal frequencies for the different drilling locations

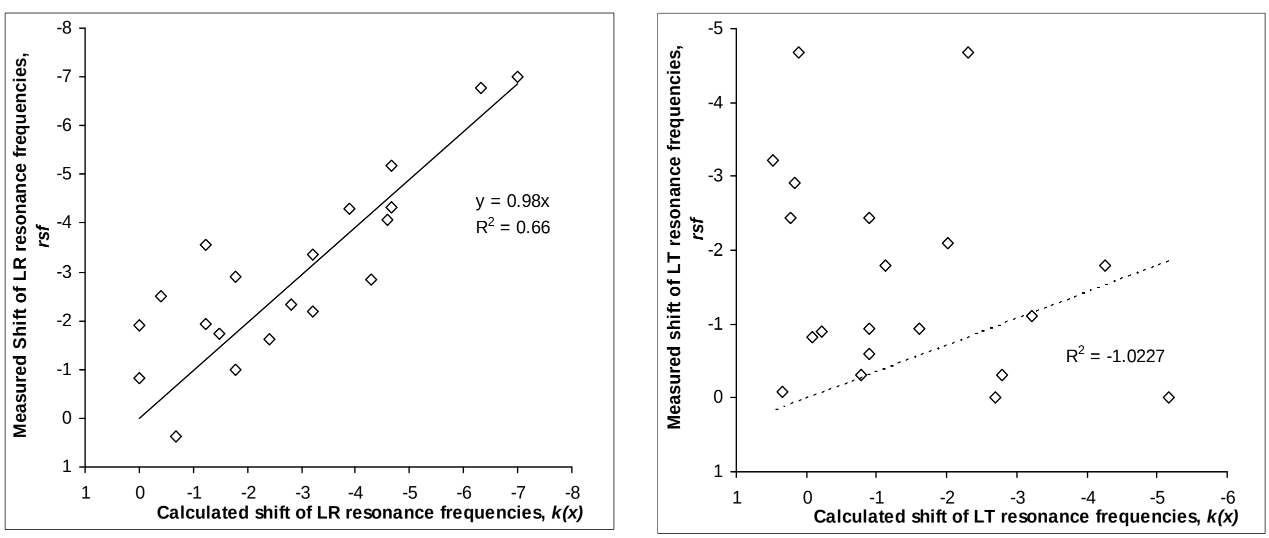


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Fig. 3. Correlations between measured and calculated relative shifts of LR (a) and LT (b) modal frequencies

This phenomenon was justified regarding the most probable coincidence in the hole orientations with the bending neuter axis in LT vibration form (Fig. 1). Only the LR flexural vibration was considered next to calculate the coincidence factor in Eq. 3 and plotted against the relative distance from an end in Fig. 5 based on the total four initial modes of vibration using the averages of the replications in individual groups. Considering an acceptable connivance, the calculated coincidence factor was capable of locating the hole in terms of relative distance from an end. So, the developed methodology of flexural vibration should be promising to combine with the longitudinal vibration technique, especially when more than one or two initial resonance frequencies are not easily obtained in longitudinal vibration due to the sizes of the relatively smaller specimens (same as the specimen sizes under this study).

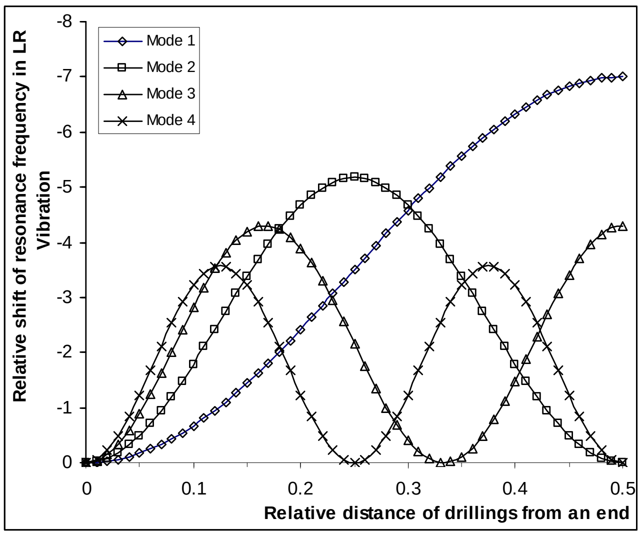

Fig. 4. The relative shift of resonance frequency by a hole, calculated from the transfer matrix method in approximated sinusoidal curves

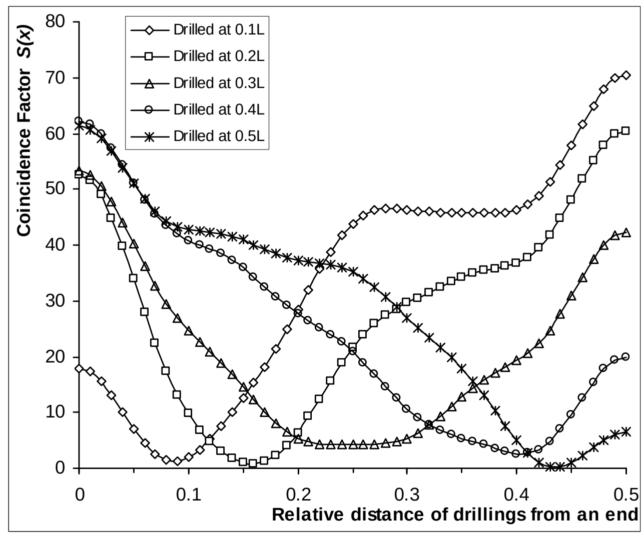

Fig. 5. Identification of a single hole drilled at 0.1, 0.2, 0.3, 0.4, and 0.5 span of the beam

As a reminder, when the resonance frequencies of a beam before and after the presence of a defect were known, the defect position could successfully be estimated with this introduced methodology. This approach seemed to be applicable only for artificial simulations of the defects, while the most difficult problem in this methodology was the unknown defect-free frequencies of an existing naturally defective timber. As proposed by Sobue et al. (2010), the fundamental resonance frequency (standard frequency, f^{st}) in the defect-free condition for individual pieces of defected lumber was estimated using the maximum frequency in the normalized resonance frequency f_n/r_n among the four vibration modes.

$$f^{st}=Max\,(f_n/n;\ n=1,2,3,4) \tag{4}$$

$$rsf_n^{st}=\frac{f_n-r_n.f^{st}}{r_n.f^{st}}\times 100 \tag{5}$$

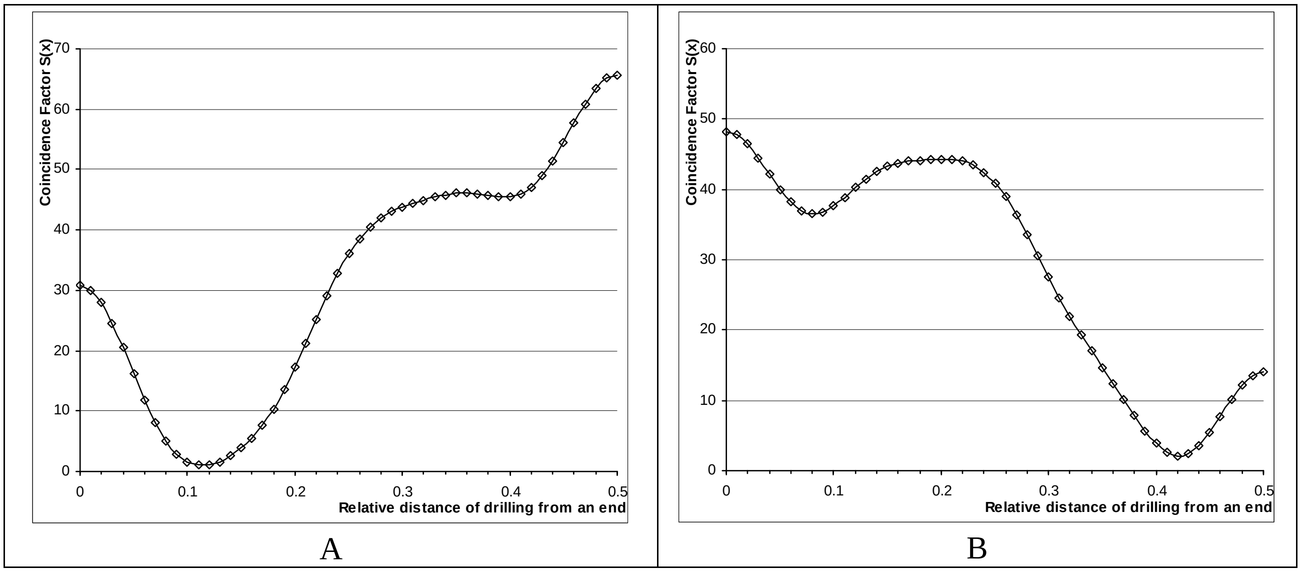

Fig. 6. Identification of drilling location at the relative distance of 0.15 (a) and 0.45 (b) from an end in the extra beams with unknown modal frequencies in their defect-free conditions

The procedure was applied to the two remaining specimens to check the efficiency of the proposed methodology. Similar holes were drilled at the 0.15 and 0.45 relative distances in each additional beam, and the resonance frequencies were evaluated in free LR flexural vibration test. Using Eq. 4 and Eq. 5, the relative shifts of the frequencies were estimated and applied to the calculations of the coincidence factor *S(x)*, which were plotted in Figs. 6a and 6b.

Using the present method of least squares while considering a small connivance, the defect position was properly identified in specimens similar to the studied beech timbers, but when the methodology was applied to a piece of pine wood with similar dimensions to the studied specimens, the defect position could not be efficiently located. In other words, there would be other effective factors among the variety of the species, such as density, which could be considered in future investigations.

CONCLUSIONS

Relative frequency shifts of the free flexural vibration was studied to generate an identification factor in the position of a single defect in timber beams of oriental beech. Using method of least squares and transfer matrix method in flexural vibration test, following the approach proposed by Sobue et al. (2010) for the longitudinal vibration, an inexpensive methodology is suggested to locate the defect position. Based on this approach it was concluded that:

1. Similar to the longitudinal vibration test, the shifts of flexural modal frequencies due to the defects presence in a beam is identifiable.
2. When the defect position mostly coincides with the neuter axis of bending, the flexural vibration is not efficient enough to follow the relative shifts of the

dynamic responses of the beam. Rotating the flexural axis of the beam in 90 degrees may be the solution.
3. The transfer matrix of relative shifts of modal frequencies due to the defect position displacement is well fitted with sinusoidal patterns in the flexural vibration technique.
4. The method of least squares, resulting from the measured and calculated relative shifts of flexural modal frequencies, is also applicable to locate the defects in wood.
5. There are various effective factors among the variety of species that may affect the present approach; therefore, they are recommended for future studies. In other words, a global research is necessary to take a reasonable variety of wood species into account.
6. Identification of more modal frequencies is possible in flexural rather than longitudinal vibration. Due to lower frequencies in flexural vibration, which is identifiable with inexpensive receivers, such as a conventional microphone, the flexural methodology might be preferred.
7. The coincidence factor in longitudinal vibration was promising enough to estimate the position of the defect, but its combination with the flexural vibration might increase the degree of confidence in the identification of wood defects.
8. Nevertheless, the methodology developed in this study was not suitable for the LT resonance frequency and for the different species. So, the testing of multiple species remains as an important concern, awaiting the continuation of this approach using some more species diversities with reasonable intervals of specific gravities and specimen sizes.

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