

# Detection and Location of Defects in Laminated Veneer Lumber by Wavelet Package Analysis

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Large numbers of vibration signals of wood-based panels are unsteady and complicated, which means that detection can be difficult. The wavelet transform is an effective method to detect these signals, which are otherwise difficult to detect using the Fast Fourier Transform (FFT). This paper presents a study on nondestructive detection of bubble defects seen in poplar laminated veneer lumber (LVL) using a combination of modal analysis and wavelet transform. The energy spectrum of wavelet packet decomposition due to a vibration signal is investigated. The vibration nondestructive test is used to study the relationship between bubble and changes of LVL physical properties. Results show that a bubble defect leads to a variation of energy dissipation in LVL vibration, and it is mode-dependent. For relatively small bubbles, the bubble-induced changes in natural frequencies are too small to be detected by the nondestructive method. However, by analyzing the energy spectrum of wavelet packet decomposition, smaller bubbles can be detected using the nondestructive vibration signals. The position and degree of defects can be ascertained by the wavelet packet energy curvature method at the same time.

*Keywords:* LVL; Defect detection; Non-destructive technique; Natural frequency; Wavelet transform; Energy curvature

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## INTRODUCTION

In recent years, computer technology and signal processing technology provide researchers with additional solutions, ideas, and methods for damage identification. Such methods include modal analysis, wavelet theory, neural networks, and genetic algorithms (Passialis and Adamopoulos 2002; Tsuchikawa *et al.* 2003). These methods have their own unique advantages, and their applications to address the structural damage identification are new solutions (Ross *et al.* 1999; Salawu 1997; Wang and Winistorfer 2003; Zou *et al.* 2003). The wavelet analysis method obtains the information effectively because of improved time resolution at high-frequency domains and frequency resolution at low-frequency domains (Peng *et al.* 2005). As a new algorithm for signal processing and data compression, wavelet transform has been used for multi-resolution signal representation since the last decade. Energy conservation is satisfied during these transformations, so the waveforms can be normalized as unit vectors. Therefore, wavelet packet decomposition has an effective application to analysis on vibration response, especially non-steady signals (Wei *et al.* 2004).

Defects in wood materials include natural, drying, machining, and biological hazards defects (Wang *et al.* 2001). These defects adversely affect the wood material,

which results in reduced timber value (Teixeira and Moslemi 2001; Tiitta *et al.* 2001). To save and improve the utilization of timber, there are many ways to detect wood defects. The traditional detection method is destructive testing, but this method destroys the materials and can cause waste. The nondestructive evaluation technique is an effective method to detect defects quickly and exactly (Kessler *et al.* 2002; Sfarra *et al.* 2013). The defects of wood will change the modal parameter that reflects the change in sensitivity of the structure parameter (Machado *et al.* 2004). Using documented theory and test results, it has been demonstrated that timber can be nondestructively tested by vibration mode analysis, which can reflect the modal parameter change (Kodama *et al.* 2001). The acquisition and analysis of signals is important in vibration nondestructive evaluation (Colombo *et al.* 2003). Substantial damage will result from the development or accumulation of very tiny damage; it is thus very important and meaningful to find the damage at an early development stage. The conventional signal analysis method is based on Fast Fourier Transform (FFT), which can effectively be applied in steady and periodic signals (Hilbers *et al.* 2012; Teixeira and Moslemi 2001). However, when considering a small amount of damage, the damage-induced changes of physical properties in composites are always too insignificant to discover the damage using the FFT-based method (Wei *et al.* 2004).

Wavelet analysis is a more effective method than the FFT method to process unsteady signals, such as the non-destructive vibration signals of timber (Guo and Peng 2007; Hu and Afzal 2006). Few publications can be found about its application to vibration-based damage detection of wood-based composites (Beall 2000; Roohnia *et al.* 2011). Despite the extensive studies of vibration nondestructive analysis on damaged wood-based composites, only a few effective and practical techniques were found for position and degree identification of wood-based composites damage (Choi *et al.* 2007; Roohnia *et al.* 2014; Reinprecht and Hibký 2011). Modal analyses has proven to be an effective method for defects detection (Khademieslam *et al.* 2011; Ma *et al.* 2008; Roohnia *et al.* 2011; Song *et al.* 2011). Therefore, this paper focuses on the study of a practical method for effective detection of bubble defects in poplar LVL by combining wavelet packet energy curvature method with 3-scale wavelet packet decomposition of nondestructive vibration signals.

## EXPERIMENTAL

### Materials

Poplar veneers used in this study were obtained from the Shuangfeng district in Heilongjiang, China. The average density of the single plate was  $0.41 \text{ kg/m}^3$ , the average thickness was 2 mm, and the moisture content was 8%. Urea formaldehyde resin glue ( $160 \text{ g/m}^2$ ) was applied to a single surface of each layer following the manufacturing company's recommendations. The glued layers were assembled together and were pressed in a pressing machine for 20 min under a pressure of 1 MPa and a temperature of  $100 \text{ }^\circ\text{C}$  to form an 11-ply sample. The dimensions of the final layer were  $500 \times 300 \times 22 \text{ mm}$  (length  $\times$  width  $\times$  thickness). The average density of LVL specimen is  $0.44 \text{ kg/m}^3$ . A bubble defect was simulated by inserting a polyester film with a thickness of 0.02 mm into the plate. Each polyester film was inserted between the fifth and sixth layers (counted from the top of the LVL) when the samples were fabricated. In the defect location test, bubble defects with an area of  $80 \times 40 \text{ mm}$  were inserted in the left, middle,

and right end of the LVL specimen, as shown in Fig. 1. In the defect degree test, the bubble areas were A, B, and C ( $60 \times 100$  mm,  $90 \times 100$  mm, and  $150 \times 100$  mm) in the center of LVL sample, respectively.

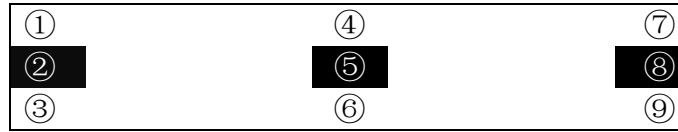


Fig. 1. Defects in LVL specimen

## Methods

The transverse vibration nondestructive testing of LVL specimens was carried out using the FFT natural frequency testing system (AD-3452; Onokazu Company, Japan). This test involved supporting the sample over four tripods. One of the tripods had a sensor that transmitted the transverse vibration signal to a computer (Halabe *et al.* 1997). The specimen was successive stroked from point 1 to point 8 (Fig. 2a) and point 1 to point 6 (Fig. 2b) to produce the pulse signal. As the sampling frequency is an important task (Roohnia *et al.* 2013; Sobue *et al.* 2010), it was fixed at 3.2 KHz, and there were 2048 sampling points. The mechanical static bending apparatus used in this study conforms to the national standard of the People Republic of China (GB/T 17657-1999). A weighing balance was used to measure the sample density. Samples were placed in a constant temperature and humid room at 20 °C and 65% RH, respectively.

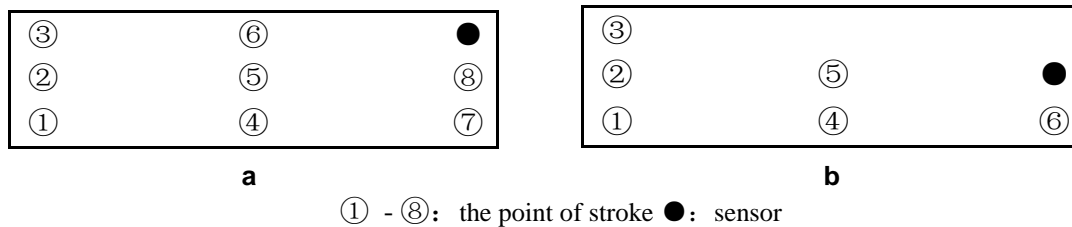


Fig. 2. Vibration nondestructive test with four supported sides

## RESULTS AND DISCUSSION

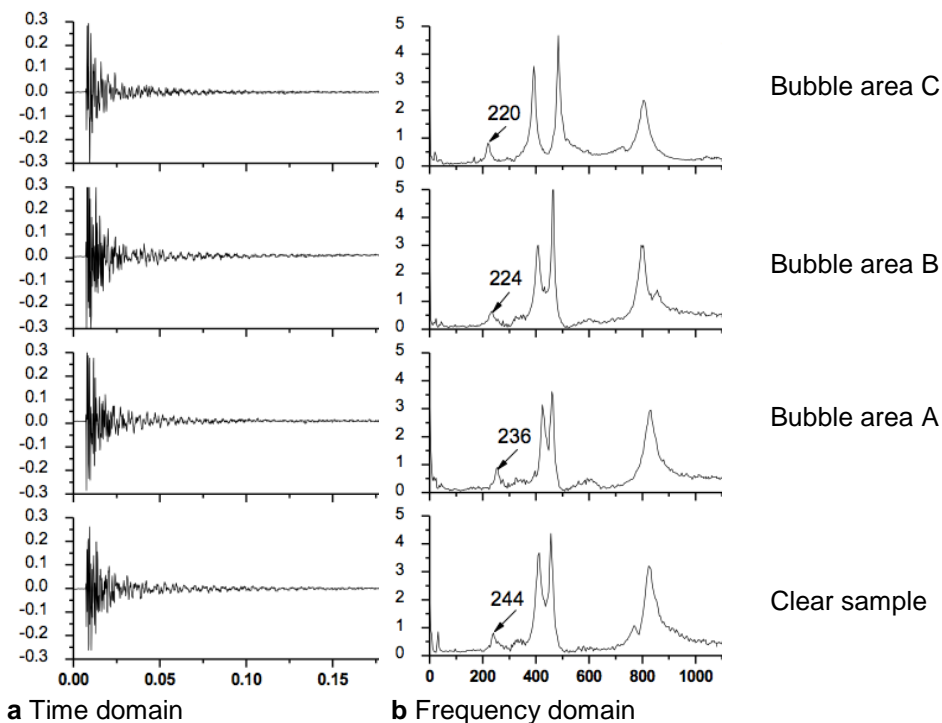
### Bubble-induced Variation of Natural Frequency

The structural damage will affect the associated physical parameters (Shi *et al.* 1998). There are different relationships between the defects and physical parameters, and only those physical parameters that are sensitive to defects can be used for structural defects detection (Johnson 1988). The key to research in structural defect detection is to find the sensitive parameter (Sun and Chang 2002). The response frequency of signals will change in the case of structural damage (Salawu 1997). The time domain and frequency domain of vibration nondestructive signals of LVL were analyzed with the LabVIEW software. The bubble defect cannot be tested by time domain, which has little difference between the clear and defect specimen, as shown in Fig. 3a. In the time domain, the amplitude of bubble specimens decay more slowly than that of clear specimens, which is not very obvious. The frequencies of specimens were compared using FFT, as shown in Fig. 3b. The frequencies of bubble specimens were reduced when

compared to the clear specimens in the first modes. Table 1 lists the natural frequencies for the LVL with bubble defect of different areas. It can be seen that with the increase in bubble area, the natural frequency will decrease. The bubble-induced change of natural is slight and therefore is difficult to measure.

**Table 1.** Variation in Frequency at Different Defect Levels

Mode	1	2	3	4	5	6
Clear sample	244	412	464	824	1200	1300
Bubble degree A	236	408	456	796	1176	1280
Bubble degree B	224	380	416	756	1056	1200
Bubble degree C	220	372	400	730	1000	1100



**Fig. 3.** (a) Time and (b) frequency domain of signal of different bubble degree specimen

Figure 4 shows the percentage changes of natural frequencies with bubble areas. It is obvious that the absolute values increase with the bubble area. It is also seen that the decrease in natural frequency is not similar for different modes. When the bubble area was  $60 \times 100$  mm, the bubble-induced change of natural frequencies were smallest, which indicates that the bubble-induced frequency change is insignificant for small bubble. In addition to damage, other factors such as fabricating process of samples, support, and experimental error can also lead to the change in natural frequencies. Therefore, it is indispensable to analyze the bubble-induced changes of other parameters for effective detection of bubble in LVL.

### Wavelet Packet Decomposition of Vibration Signals

The bubble is experimentally determined according to the variation of energy dissipation in the LVL during vibration, and acceleration response to random excitation is

measured (Wei *et al.* 2004). The sampling frequency was 3.2 kHz. The Daubechies wavelet packet decomposition method was applied to these signals. The signals were decomposed to eight equal bandwidth frequency in [0, 1.6 kHz], namely [0, 200 Hz], [200 Hz, 400 kHz], [400, 600 Hz], [600, 800 Hz], [800, 1000 Hz], [1, 1.2 kHz], [1.2, 1.4 kHz], and [1.4, 1.6 kHz]. The sum of percentage of the energy variation in every subspace over the total energy variation in the third layer was obtained, and results are shown in Fig. 5.

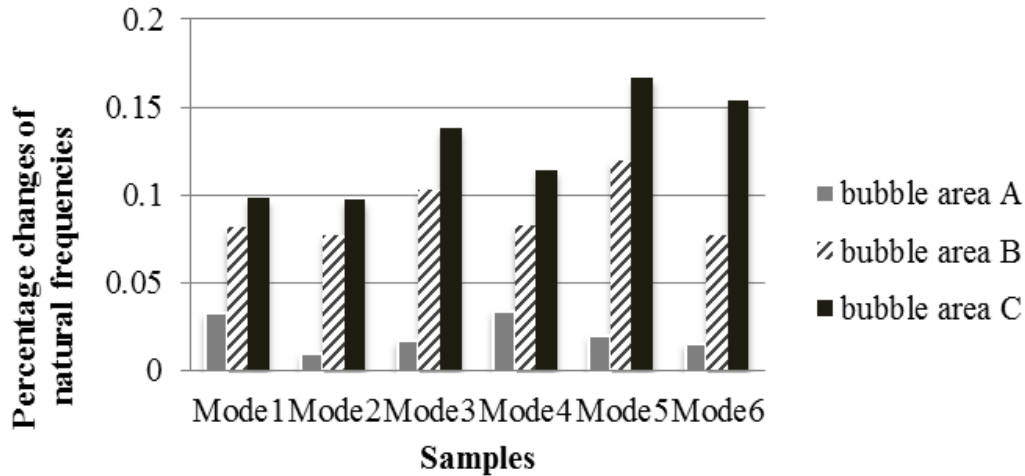


Fig. 4. Percentage changes of natural frequencies for LVL with bubble for different areas

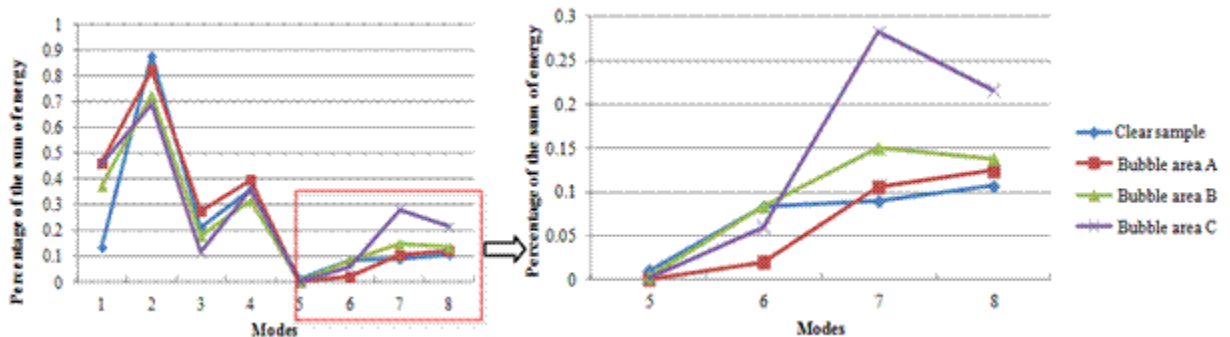


Fig. 5. The percentage of the sum of energy variation of the signal after wavelet packet decomposition

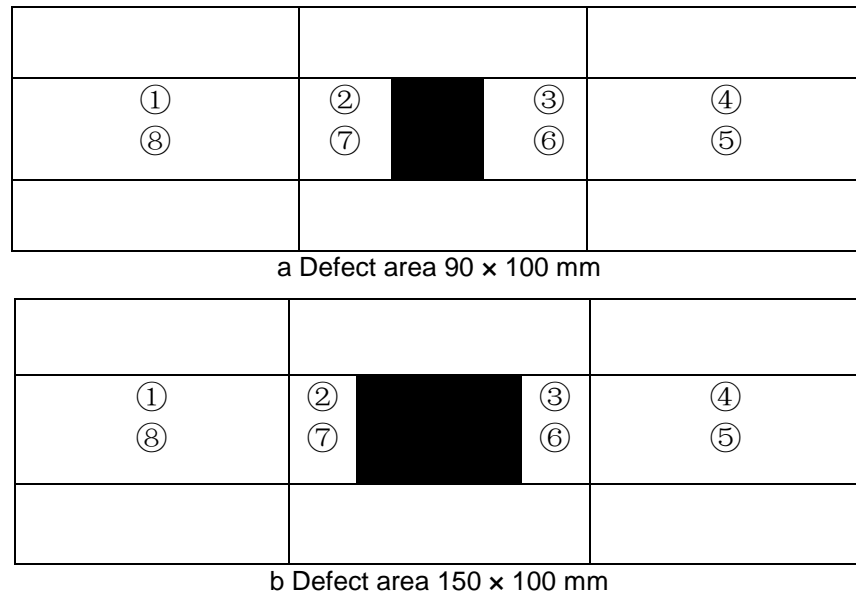
When the LVL is bubbled, variations exist. In the second frequency components [200, 400 Hz], the signal energy percentage of clear specimen was higher than that of the bubble specimen. However, the resonant frequency of the bubble specimen was less than the clear specimen. As the bubble degree increased, their energy percentage decreased, which is in line with their first order resonant frequency values. The influence of bubble defect on vibration frequency increased with frequency. The effect of damage on high modes is more sensitive than the low modes (Salawu 1997). This also shows that with the increase of bubble size, response signals with higher frequencies contribute more to the variation of energy dissipation induced by bubbles. In the high frequency modes, the fifth

and sixth frequency modes displayed little difference. However, the energy percentage increased with the degree of bubble defects for the seventh [1200, 1400 Hz] and eighth modes [1400, 1600 Hz]. This result shows that the higher modes of bubble defects were more sensitive than the low modes.

Unlike the natural frequency, the energy variation of signals decomposed by wavelet packets is measurable and obvious enough to identify the bubble even for the smallest size. Thus, combined with the numerical analysis, the bubble-induced energy variation obtained by wavelet packet decomposition can be an effective method to identify small bubble defects.

**Wavelet Packet Energy Curvature**

The energy percentage based on wavelet packet analysis can determine the degree of defects, but could not determine the exact defect location. This method could not determine the location and the degree at the same time, and was unable to determine the existence of multiple defects. The damage of a structure will affect the signal components energy curvature of wavelet packet (Han *et al.* 2005). The bubble defects of LVL were detected by wavelet packet energy curvature method. The areas of bubbles were 90 × 100 mm and 150 × 100 mm, respectively, as shown in Fig. 6. The vibration signals of clear specimen and bubble specimen were decomposed with a three layer wavelet packet method. The damage sensitive coefficient of bubble sample is the fourth frequency, as shown in Table 2.



**Fig. 6.** Defects degree and position of LVL specimen

**Table 2.** Sensitive Coefficient of Structural Damage

F(t)	1	2	3	4	5	6	7	8
C	0.318	0.606	0.460	0.838	0.064	0.311	0.147	0.034

The energy curvature change of the fourth wavelet packet is shown in Fig. 7. The wavelet packet energy curvature changes with the increase of the bubble degree, and the curve is sensitive to the degree of defect. The energy curvature change is largest between the modes of 2 to 3 and 6 to 7 (Fig. 6). The degree and position of bubble defects can be detected by the wavelet packet energy curvature.

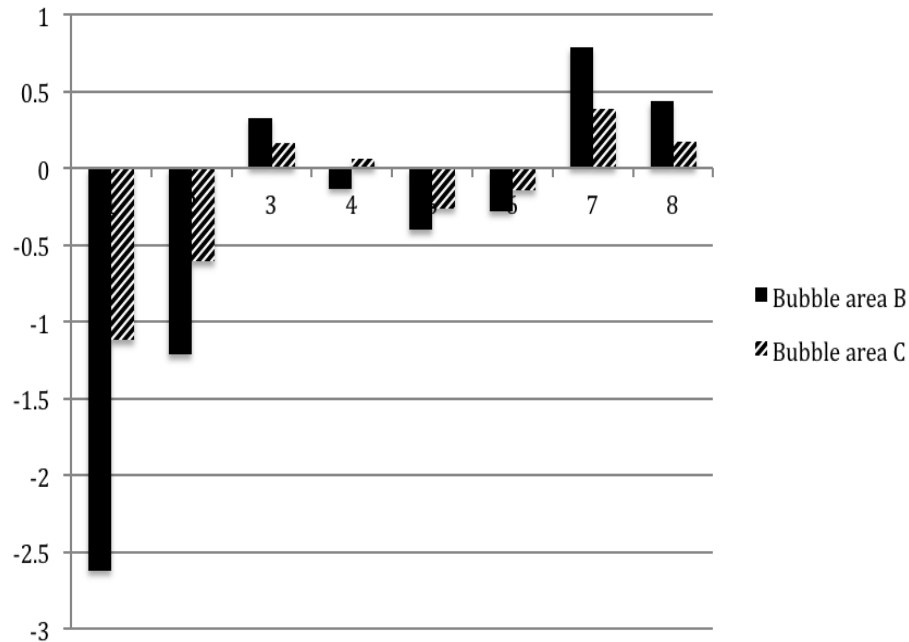


Fig. 7. Wavelet packet energy curvature of LVL samples with different bubble defect areas

## CONCLUSIONS

1. The natural frequencies are changed when a bubble defect is present in laminated veneer lumber (LVL), and this change is too slight to be practically determined for small bubbles.
2. The bubble-induced change can be determined by measuring the signal response when an energy spectrum wavelet packet decomposition is used as the index of bubble-induced variation.
3. The wavelet package sensitivity to the frequency of defects is determined by the sensitivity coefficient. The position and degree of defects can be ascertained by analysis of the wavelet energy's curvature signal at the same time.

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## REFERENCES CITED

- Beall, F. C. (2000). "Subsurface sensing of properties and defects in wood and wood products," *Subsurface Sensing Technologies and Applications* 1(2), 181-204.
- Choi, F. C., Li, J., Samali, B., and Crews, K. (2007). "Application of modal-based damage-detection method to locate and evaluate damage in timber beams," *Journal of Wood Science* 53(5), 394-400.
- Colombo, I. S., Main, I., and Forde, M. (2003). "Assessing damage of reinforced concrete beam using "b-value" analysis of acoustic emission signals," *Journal of Materials in Civil Engineering* 15(3), 280-286.
- Guo, D., and Peng, Z. (2007). "Vibration analysis of a cracked rotor using Hilbert-Huang transform," *Mechanical Systems and Signal Processing* 21(8), 3030-3041.
- Halabe, U. B., Bidigalu, G. M., GangaRao, H. V., and Ross, R. J. (1997). "Nondestructive evaluation of green wood using stress wave and transverse vibration techniques," *Materials Evaluation* 55(9), 1013-1018.
- Han, J.-G., Ren, W.-X., and Sun, Z.-S. (2005). "Wavelet packet based damage identification of beam structures," *International Journal of Solids and Structures* 42(26), 6610-6627.
- Hilbers, U., Thoemen, H., Hasener, J., and Fruehwald, A. (2012). "Effects of panel density and particle type on the ultrasonic transmission through wood-based panels," *Wood Science and Technology* 46(4), 685-698.
- Hu, C., and Afzal, M. T. (2006). "A wavelet analysis-based approach for damage localization in wood beams," *Journal of Wood Science* 52(5), 456-460.
- Johnson, R. (1988). "Relationship between defect energies and embedded-atom-method parameters," *Physical Review B* 37(11), 6121.
- Kessler, S. S., Spearing, S. M., and Soutis, C. (2002). "Damage detection in composite materials using Lamb wave methods," *Smart Materials and Structures* 11(2), 269-278.
- Khademieslam, H., Hemmasi, A. H., Abdollahiansohi, A. M., Roohnia, M., and Talaiepour, M. (2011). "Nondestructive evaluation of the effect of hole diameter on Young's modulus of wood using flexural vibration," *World Applied Sciences Journal* 13(1), 66-72.
- Kodama, Y., Zhang, Z., and Kawabata, H. (2001). "Evaluation of wood quality by wavelet analysis II. Estimation of knot size," *Japan Wood Research Society* 47(6), 473-478.
- Ma, X.-Q., Morita, C., Sakiyama, T., Matsuda, H., and Huang, M. (2008). "Study on free vibration of plates with variable thickness and a hole defect," *Reports of the Faculty of Engineering, Nagasaki University* 38(70), 13-19.
- Machado, J. S., Sardinha, R. A., and Cruz, H. P. (2004). "Feasibility of automatic detection of knots in maritime pine timber by acousto-ultrasonic scanning," *Wood Science and Technology* 38(4), 277-284.
- Passialis, C., and Adamopoulos, S. (2002). "A comparison of three NDT methods for determining the modulus of elasticity in flexure of fir and black locust small clear wood specimens," *European Journal of Wood and Wood Products* 60(5), 323-324.



- Peng, Z., Tse, P. W., and Chu, F. (2005). "A comparison study of improved Hilbert-Huang transform and wavelet transform: Application to fault diagnosis for rolling bearing," *Mechanical Systems and Signal Processing* 19(5), 974-988.
- Reinprecht, L., and Hibký, M. (2011). "The type and degree of decay in spruce wood analyzed by the ultrasonic method in three anatomical directions," *BioResources* 6(4), 4953-4968.
- Roohnia, M., Manouchehri, N., Tajdini, A., Yaghmaeipour, S., and Bayramzadeh, V. (2011). "Modal frequencies to estimate the defect position in a flexural wooden beam," *BioResources* 6(4), 3676-3686.
- Roohnia, M., Alavi, T., Seyed, E., Hossein, M., Brancheriau, L., and Tajdini, A. (2011). "Dynamic modulus of elasticity of drilled wooden beams," *Nondestructive Testing and Evaluation* 26(2), 141-153.
- Roohnia, M., Yaghmaeipour, A., Kubojima, Y., and Tajdini, A. (2013). "Free vibration of both-ends clamped wooden beams: Is it potentially applicable as an in situ assessment method?," *Turkish Journal of Agriculture and Forestry* 37(1), 121-125.
- Roohnia, M., and Tajdini, A. (2014). "Identification of the severity and position of a single defect in a wooden beam," *BioResources* 9(2), 3428-3438.
- Ross, R. J., Willits, S. W., Von Segen, W., Black, T., Brashaw, B. K., and Pellerin, R. F. (1999). "A stress wave based approach to NDE of logs for assessing potential veneer quality. Part 1. Small-diameter ponderosa pine," *Forest Products Journal* 49(11-12), 60-62.
- Salawu, O. (1997). "Detection of structural damage through changes in frequency: A review," *Engineering Structures* 19(9), 718-723.
- Sferra, S., Theodorakeas, P., Avdelidis, N. P., and Kouli, M. (2013). "Thermographic, ultrasonic and optical methods: A new dimension in veneered wood diagnostics," *Russian Journal of Nondestructive Testing* 49 (4), 234 - 250
- Shi, Z., Law, S., and Zhang, L. (1998). "Structural damage localization from modal strain energy change," *Journal of Sound and Vibration* 218(5), 825-844.
- Song, S.-Q., Xu, H.-D., and Wang, L.-H. (2011). "The application of modal analysis in hole-defect in lumber," *Key Engineering Materials* 467-469, 1776-1780.
- Sobue, N., Fujita, M., Nakano, A., and Suzuki, T. (2010). "Identification of defect position in a wooden beam from the power spectrum of longitudinal vibration," *Journal of Wood Science* 56(2), 112-117.
- Sun, Z., and Chang, C. (2002). "Structural damage assessment based on wavelet packet transform," *Journal of Structural Engineering* 128(10), 1354-1361.
- Teixeira, D. E., and Moslemi, A. (2001). "Assessing modulus of elasticity of wood-fiber cement (WFC) sheets using nondestructive evaluation (NDE)," *Bioresource Technology* 79(2), 193-198.
- Tiitta, M., Beall, F., and Biernacki, J. (2001). "Classification study for using acoustic-ultrasonics to detect internal decay in glulam beams," *Wood Science and Technology* 35(1-2), 85-96.
- Tsuchikawa, S., Inoue, K., Noma, J., and Hayashi, K. (2003). "Application of near-infrared spectroscopy to wood discrimination," *Journal of Wood Science* 49(1), 29-35.
- Wang, J., Biernacki, J., and Lam, F. (2001). "Nondestructive evaluation of veneer quality using acoustic wave measurements," *Wood Science and Technology* 34(6), 505-516.

- Wang, S., and Winistorfer, P. M. (2003). "An optical technique for determination of layer thickness swell of MDF and OSB," *Forest Products Journal* 53(9), 64-71.
- Wei, Z., Yam, L., and Cheng, L. (2004). "Detection of internal delamination in multi-layer composites using wavelet packets combined with modal parameter analysis," *Composite Structures* 64(3), 377-387.
- Zou, G., Naghipour, M., and Taheri, F. (2003). "A nondestructive method for evaluating natural frequency of glued-laminated beams reinforced with GRP," *Nondestructive Testing and Evaluation* 19(1-2), 53-65.

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