Application of Vibrational Methods in Wood Performance Testing: A Short Review

Jiawen Shi, Shiyan Yin, Wenlan Huang, and Bin Na *

Vibrational methods, which are widely recognized non-destructive testing (NDT) techniques for timber, have garnered significant attention due to their ease of use, broad applicability, and reliable data output. These methods analyze the vibrational response of wood to external stimuli to assess its mechanical properties and internal structure. With advancements in sensor technology, signal processing, and computer simulation, the role of the vibrational methods in timber inspection has been largely expanded, enhancing both the scientific application and quality assurance of timber. This paper provides a comprehensive review of applications of vibrational methods in timber performance evaluation, focusing on its vibrational characteristics, underlying principles, and utility in detecting the physical and mechanical properties as well as internal defects of timber. Furthermore, potential future trends are discussed. Through analysis and research, valuable insights into the evolution of non-destructive timber testing technology are aimed to be provided by this review, and technological innovation in the timber industry is encouraged.

DOI: 10.15376/biores.20.2.Shi

Keywords: Vibration method; Modal analysis; Mechanical properties; Defect detection; Machine learning

*Contact information: College of Materials Science and Engineering, Nanjing Forestry University, Nanjing 210037, China; *Corresponding author: nabin8691@126.com*

INTRODUCTION

Timber is recognized as a sustainable and eco-friendly resource. Timber products are widely used across various industries due to wood's carbon sequestration ability, environmental benefits, and ease of processing. With industrialization advancing, the global demand for timber continues to grow. However, in China, limited forest resources and low forest coverage have resulted in a widening gap between the supply and demand for timber (Liu 2014). Consequently, the optimization of timber utilization has become crucial, and the implementation of precise timber testing methods is considered a highly effective strategy. Since the 1960s, numerous non-destructive testing (NDT) techniques have been developed to assess timber performance without compromising its physical and mechanical properties or internal structure (Xiong *et al.* 2023).

Non-destructive testing (NDT) methods allow for objects to remain in service without interruption following examination. The responses of the objects to various stimuli, such as light, electricity, magnetism, and sound, are utilized by these techniques (Wang *et al.* 2022). Widely used NDT methods include stress wave analysis, ultrasonics, microdrill impedance measurement, radiography, near-infrared (NIR) spectroscopy, and vibration testing. The stress wave technique is based on the propagation of stress waves through materials. Ultrasonic testing is highly effective at identifying minute internal flaws but requires specialized equipment and expertise. The microdrill impedance method provides localized assessment, though a risk of damaging the wood is posed. Strict safety measures to protect against radiation are required by radiographic testing, which involves the use of costly, specialized equipment. The near-infrared spectroscopy detection method is a new non-destructive testing technique that utilizes the anharmonicity of wood molecules, causing their vibrations to transition from the ground state to higher energy levels. This method can evaluate the physical and mechanical properties, as well as the chemical composition of wood and processed wood (Chen *et al.* 2022).

Vibrational methods utilize the dynamic responses of wood to external stimuli to reveal its dynamic characteristics. Through focusing on the vibrational performance of the entire structure, key mechanical properties of wood, such as strength and modulus of elasticity, are assessed *via* the measurement of natural frequencies, vibrational modes, and damping (Hu *et al.* 2002). Noted for its simplicity in operation, equipment setup, and data analysis, significant advantages are offered by vibrational methods: they are non-destructive, highly sensitive, reliable, and accurate. These attributes make them ideal for evaluating a wide range of wood products, from logs and sawn timber to laminated timber. The theoretical and methodological framework of vibrational methods have been further refined through the integration of advanced sensor technology, electronics, signal processing, fast Fourier transform (FFT), modal analysis, and computer simulation (Tao *et al.* 2023).

DYNAMIC CHARACTERISTICS OF WOOD

The dynamic properties of wood are intrinsically linked to its natural frequency, a parameter that is significantly influenced by factors such as wood density, moisture content, elastic modulus, and the presence of internal defects.

Density, defined as the mass of wood per unit volume, is recognized as playing a crucial role in determining its vibrational properties. Generally, wood with higher density is observed to exhibit a greater natural frequency. This is because denser wood possesses more mass and greater inertia within a given volume, leading to a higher vibrational frequency when subjected to the same external force. Through using vibrational methods to measure the natural frequency, the density of the wood can be calculated through the development of a mathematical model that correlates these two properties.

The modulus of elasticity, also referred to as stiffness, is significantly influenced by the natural frequency of wood. This property is used to quantify wood's resistance to deformation under external forces and is essential for evaluating its load bearing and service capabilities. The modulus of elasticity is determined by the structural and chemical composition of the wood, including the proportions of cellulose, hemicellulose, and lignin, as well as their molecular arrangement. The orientation of the wood grain, or the direction of fiber alignment, is found to substantially affect its vibrational properties. Vibration along the grain (longitudinal direction) is considered more efficient due to the compact inter-fiber bonds, whereas transverse vibration (across the grain) is regarded as less efficient due to the disrupted inter-fiber connections. Additionally, the porous structure and anisotropic nature of wood are recognized to influence its vibrational characteristics, impacting how vibrations are transmitted and distributed. Through employing vibrational methods to measure the natural frequency, the dynamic modulus of elasticity can be calculated and analyzed in relation to the static flexural modulus, highlighting their interaction (Wang 2007). Research indicates that the dynamic modulus of elasticity typically exceeds the static flexural modulus, and the flexural strength of wood can be predicted using a linear regression model (Hua *et al.* 2015).

The moisture content of wood, defined as the ratio of water weight to the mass of dry wood, is significantly affected by its vibrational behavior. Variations in moisture content are found to directly influence the density, modulus of elasticity, and strength of wood, thereby impacting its vibrational properties. As moisture content increases, the density of wood is observed to rise, as water fills the cell walls and interiors, leading to an increase in both total weight and volume. However, this increase is not uniform and can introduce inhomogeneities within the wood's internal structure. At the same time, higher moisture content is known to weaken the hydrogen bonds between cellulose and hemicellulose molecules, reducing the rigidity of the wood. Typically, below the fiber saturation point (approximately 30%), wood strength is seen to decrease as moisture content rises. Changes in moisture content can be inferred from variations in vibrational characteristics that are detected through vibrational methods.

Wood defects are known to significantly affect its vibrational characteristics and can be categorized into three main types: natural, biological, and processing-related defects. These defects arise either from physiological factors during tree growth or from human activities during production, influencing the wood's appearance, workability, and mechanical properties (Wang *et al.* 1994). Intrinsic defects, such as knots, growth cracks, and reaction wood—often resulting from genetic and environmental factors—are found to reduce the dynamic modulus of elasticity and tensile strength along the grain, thereby compromising the wood's structural integrity. Biological defects, including decay, discoloration, and infestations by fungi, bacteria, and insects, not only diminish the wood's integrity and appearance but also degrade its physical and mechanical properties. Processing-induced defects, such as drying cracks, warping, and saw kerf injuries, are observed to occur during manufacturing and affect the wood's shape, dimensions, and usability (Niu and Chen 2014). Vibrational analysis is recognized as a powerful tool for detecting these defects and assessing their impact on wood's mechanical properties. For instance, it has been shown that the presence of knots and voids decreases both the dynamic modulus of elasticity and the natural frequency of wood (Cui 2006). Through analyzing vibration signals, these defects can be identified, and their specific effects on the wood's performance in various applications can be quantified.

VIBRATIONAL METHODOLOGIES: AN OVERVIEW

Vibrational methods, which can be classed as non-destructive testing (NDT), are being employed to assess the internal properties of wood. This technique is based on the principle of inducing vibrations in the wood using various excitation methods, such as steady-state sinusoidal, transient, and random signals. These vibrations are detected by sensors, which capture and transmit the signals for amplification and recording. The recorded data are analyzed to deduce the internal characteristics of the wood.

Steady-state sinusoidal excitation involves the application of a sinusoidal force at a constant frequency to stimulate wood, producing a stable vibrational signal that is relatively straightforward to analyze. However, it may not fully replicate the complex vibration environments encountered in practical applications of wood.

In contrast, stochastic excitation is employed to simulate these complex environments by applying random forces, offering statistical insights into the wood’s response across a broad range of frequencies. This approach is particularly useful for evaluating wood performance under real-world conditions.

Transient excitation, by contrast, is widely recognized as an effective method due to its simplicity and rapid response. This technique typically involves the application of a brief force pulse, such as a knock, to induce a broad spectrum of vibrational modes. It is particularly effective for assessing the dynamic properties of wood, including its natural frequency and damping ratio. The impulsive signals generated by tapping are propagated through the wood and are shaped by its inherent properties, which are reflected in the resulting vibration signals. The analysis of these signals enables the deduction of the wood's internal characteristics. The testing apparatus typically includes pulse hammers, accelerometers, impedance converters, vibrometers, data collectors, oscilloscopes, and computers (Yang and Shen 2010).

Vibrational analysis is extensively employed in monitoring industrial machinery, with various vibrational parameters, such as displacement, phase, velocity, acceleration, and frequency, being effectively captured during machine operation. This method not only detects these parameters but also enables the determination of the dynamic characteristics of mechanical systems through excitation, including natural frequency, damping ratio, stiffness, and mode shapes (Xie 2015). In the context of wood testing, vibrational techniques are regarded as invaluable for evaluating mechanical properties and detecting defects. For instance, transverse vibrational testing is used to determine the natural frequency of wood, which facilitates the calculation of the dynamic modulus of elasticity and a comprehensive analysis of its mechanical characteristics (Beall 2000). Furthermore, by analyzing patterns in vibrational signals, defects in wood, such as knots, decay, and voids, can be identified, which disrupt the wood’s elastic modulus and vibration frequency, rendering them detectable through vibrational analysis. The theoretical framework of vibrational analysis has advanced to a sophisticated level.

Vibrational methods offer numerous significant advantages, underscoring their importance in the field of NDT. The primary benefits of this method are characterized by its non-destructive nature and inherent safety, as neither the inspected object nor the operator is damaged or subjected to safety risks. Its versatility is noted for enabling application across a wide range of materials, including metals, concrete, wood, and composites, making it a highly flexible and effective NDT technique.

The operation of vibrational methods is regarded as user-friendly, requiring only the excitation of vibrations by an external source and the subsequent recording of the response by a transducer. The output signals are then analyzed using specialized software. This simplicity is noted for significantly reducing the technical requirements for operators. The high sensitivity of vibrational methods allows for the detection of minor vibrational changes that may indicate alterations in the structure or the material’s intrinsic properties. Additionally, the real-time collection of vibrational data ensures the objectivity and accuracy of the results. Moreover, a comprehensive evaluation of the structure and the determination of critical performance indicators are facilitated through the analysis of modal parameters. This process is considered essential for overall performance assessment, defect identification, and the development of effective maintenance strategies.

APPLICATIONS OF VIBRATIONAL METHODS TO THE DETECTION OF PHYSICAL AND MECHANICAL PROPERTIES AND INTERNAL DEFECTS OF WOOD

Testing of Physical and Mechanical Properties of Wood

Since the 1970s, research on the vibrational characteristics and mechanical properties of wood has been actively engaged in by scholars worldwide. This research has significantly deepened the theoretical understanding of wood science and has led to the development of innovative methods and techniques for the non-destructive testing of wood materials.

In early studies, a vibrational method was employed by Yoshio Nakayama and colleagues to assess the mechanical properties of wood, with a computer program developed in 1975 to calculate the transverse vibrational modulus of elasticity. This marked the first application of the vibrational method in wood testing. In 1989, Bozhang Shi and his team measured the dynamic elastic modulus and internal friction of five kinds of wood samples by resonance method, attenuation method and sound velocity method, and obtained some mechanical properties of wood (Shi *et al.* 1989). In 1991, experiments with vibrational methods to evaluate the mechanical properties of wood were initiated by Ross *et al.* thereby establishing a foundation for the advancement of non-destructive testing techniques (Ross and Pellerin 1991). Subsequently, in 1988, both the modulus of elasticity (E) and shear modulus (G) were successfully measured by Sobue (1988) by integrating the bending vibrational and torsional vibration methods, significantly enhancing measurement accuracy. This advancement is crucial for improving the precision and reliability of structural designs involving wood.

In the 21st century, vibrational analysis technology has been increasingly utilized in wood inspection. In 2000, the transverse wave vibrations of wood were stimulated by Beall (2000) using a vibrational analyzer, with the modulus of elasticity and stiffness predicted through the measurement of natural frequencies and damping ratios. This work established a scientific foundation for wood processing and quality control (Beall 2000). In 2003, vibrational analysis was applied by Jaramillo *et al.* to the design of sports equipment, conducting a modal analysis of wooden baseball bats. A correlation between the vibrational modes and the bat's "sweet spot" was revealed by their findings, elucidating the bat's vibrational characteristics, and providing valuable insights for sports equipment design (Jaramillo *et al.* 2003). As technology progresses, vibrational analysis techniques are increasingly being utilized for assessing complex structures. In 2005, vibrational analysis was employed by Wang *et al.* to evaluate the stiffness of a timber bridge, revealing significant discrepancies from static load tests and identifying potential prediction errors, thereby offering valuable insights for bridge inspection (Wang *et al.* 2005). In 2006, the Fast Fourier Transform (FFT) was applied by Liu *et al.* to validate the dynamic modulus of elasticity of wood, thereby developing a novel tool for modulus of elasticity assessment (Liu *et al.* 2006). Also in 2006, it was demonstrated by Green *et al.* that the transverse vibrational method outperforms the longitudinal stress wave method in accuracy for measuring the dynamic modulus of elasticity in roundwood beams, thereby enhancing the mechanical grading of wood (Green *et al.* 2006). In 2016, it was confirmed by Teixeira (2016) that the transverse vibrational method provides more accurate measurements of the dynamic elasticity of Douglas-fir compared to the longitudinal stress wave method by correlating results with static tensile and bending moduli. By 2020, the longitudinal vibrational method was utilized by Kayode Olaoye *et al.* to determine the dynamic modulus of elasticity of white birch, with a strong correlation found with the mean static modulus of elasticity (Olaoye *et al.* 2020).

Vibrational technology was initiated for application in wood inspection in China towards the end of the 20th century. Although this initial adoption was relatively late, remarkable progress has since been made, achieving significant milestones. This trajectory indicates that the efforts in non-destructive testing technology in China are highly promising and possess substantial potential for further expansion. In 1991, groundbreaking research on the vibrational characteristics of piano soundboards was conducted by Liu Baoli and his team through modal analysis, successfully identifying the initial ten orders of natural frequency and vibrational modes. Moreover, the dynamic modulus of elasticity in spruce and musical wood was explored, with the primary resonance frequency and the associated dynamic modulus determined using resonance and pick-up techniques. These findings laid a scientific foundation for musical instrument production and underscored the early integration of vibrational technology in wood applications. This pioneering application of vibrational technology in wood inspection set a significant precedent (Liu and Hen 1991; Liu and Liu 1991). In 2001, the bending vibration method was employed by Hu and colleagues to assess the dynamic flexural and shear moduli of plywood, with these results compared to those obtained from longitudinal wave resonance and propagation methods. This comparison further confirmed the reliability of vibrational technology in wood inspection. Notably, the ability of the bending vibration method to provide accurate measurements for plywood with diverse fiber orientation angles was demonstrated, a critical factor for stress grading and quality control in wood (Hu *et al.* 2001a, 2001b).

With advancing technology, the capabilities of vibrational technology across a variety of wood species and application scenarios are increasingly being explored by Chinese researchers. In 2007, the principles of simple beam vibration were applied by Chaozhi Wang to assess the dynamic modulus of elasticity in wood, utilizing this method for stress grading (Wang 2007). In 2009, transverse vibration was employed by Houjiang Zhang and colleagues to measure the dynamic modulus of elasticity of camphor pine lumber, with these results compared to those obtained from the traditional static bending method. The findings indicated that the dynamic elastic modulus was marginally higher when determined through vibrational methods, further confirming the precision and reliability of vibrational technology in wood testing (Zhang *et al.* 2009). In 2010, a non-destructive vibrational testing system was developed by Zhu Xiaodong based on the bending vibration technique, which was instrumental in determining the dynamic elastic modulus of wood composites using virtual instrumentation. By comparing these results with data obtained from FFT analyzers and mechanical testing equipment, the accuracy and reliability of the vibrational testing system were validated (Zhu *et al.* 2010). This development marked a significant advancement toward integrating vibrational technology into wood inspection, heralding an era of automation and intelligent assessment. Also in 2010, the dynamic modulus of elasticity for PE-based wood-plastic composites and lightweight wood structural lumber was determined by Zheng Wang and his team, thus expanding the technological applications of vibrational methods (Wang *et al.* 2010a,b, 2013). In 2014, the transverse vibration method was utilized by Zhiru Zhou to ascertain the modulus of elasticity of Italian poplar timber, with these outcomes subsequently compared with measurements derived from stress wave and static four-point bending methods. This research further established the accuracy and reliability of the transverse vibration method in gauging the dynamic modulus of elasticity (Zhou *et al.* 2014). In 2015, the transverse vibration method was applied by Xijun Wang and colleagues to evaluate the modulus of elasticity of glued laminated wood beams, with their results validated through finite element analysis (Wang *et al.* 2015).

The integration of vibrational technology in wood testing has been significantly advanced in recent years. In 2016, the transverse free vibration of thin plates was utilized by Cheng Guan and colleagues to determine the natural frequency and mass of particleboards and plywood under defined support conditions. The modulus of elasticity was calculated and compared with the static modulus obtained from traditional three-point bending tests, further confirming the effectiveness of vibrational technology (Guan *et al.* 2016). Between 2016 and 2017, a novel approach to characterizing wood vibrations was introduced by Zhou *et al.* enhancing the understanding of full-sized engineered wood substrates, such as oriented strand board (OSB) and medium-density fiberboard (MDF), through experimental modal analysis and vibrational tests of elastic constants under various boundary conditions (Zhou *et al.* 2016, 2017). In 2020, a vibrational characterization of timber-concrete composite (TCC) flooring was performed by Zhong Xie *et al.*, which included modal testing and simulation of vibrations caused by human activities, offering valuable insights into the vibrational characteristics of composite flooring (Xie *et al.* 2010). In 2022, a vibrational analyzer was employed by Linbi Chen *et al.* to evaluate the damping effect of bamboo engineered materials under stochastic excitation conditions. Point-by-point excitation and multi-point testing methods were applied to measure the transfer function at resonance peaks and modal vibrational patterns, aiming to assess the material's vibration damping performance. This research established a scientific foundation for the application of bamboo engineering materials (Chen *et al.* 2022). In 2023, a cost-effective vibration testing device was developed by Liang Qi *et al.* for assessing the mechanical properties of timber beams through modal analysis. Transverse vibration tests were conducted on timber beams with single and composite layers, and Python programming was used to estimate modal frequency response functions (FRFs), thereby identifying the fundamental frequency. Moreover, the dynamic bending stiffness was calculated, presenting a new tool for analyzing the vibrational characteristics of timber beams (Qi *et al.* 2023).

In summary, significant advancements have been achieved in Chinese research on the application of vibrational technology in wood inspection, both in terms of technological innovation and application scope. These studies have not only enhanced the precision and efficiency of wood inspection but have also established a solid scientific foundation for the practical application and structural design of wood. With ongoing technological advancements, it is anticipated that an increasingly pivotal role will be played by vibrational technology in wood science, providing robust support for the sustainable and efficient utilization of wood. This progress underscores China's capacity for independent innovation and its competitiveness on the international stage in the field of non-destructive testing (NDT) technology.

Detection of Internal Wood Defects

Within the field of wood defect detection, various methodologies have been employed by researchers, including the transverse vibrational method, modal analysis, and wavelet transform techniques, to investigate essential properties of wood, such as its dynamic modulus of elasticity, natural frequency, and vibrational patterns. The primary objective of such research is to accurately detect and localize internal defects within the wood. These efforts have significantly improved the effectiveness of wood quality control and established a solid scientific foundation for the efficient utilization and preservation of wood resources.

Identifying internal defects in wood is crucial for ensuring its structural integrity and extending its service life. A pioneering study conducted by Axmon *et al.* in 2002 explored the use of modal analysis for detecting internal decay in living trees. It was found that healthy spruce exhibited a full sinusoidal vibrational pattern, while decaying samples demonstrated a reduced temporal frequency (Axmon *et al.* 2002). This offered a novel approach to non-destructive internal defect detection. In the same year, knots and grain deviations were successfully identified by Yang *et al.* by comparing actual and theoretical first-order bending vibration waveforms (Yang *et al.* 2002). Later, the elastic modulus of the wood was estimated, and defects were accurately pinpointed by Yang through the analysis of the curvature of the bending vibration waveform (Yang *et al.* 2003), highlighting the potential of vibration waveform analysis in detecting wood defects. Recognizing the limitations of time-frequency analysis for identifying internal decay, a complementary measure of surface wave propagation velocity was introduced by Axmon *et al.* (2004), significantly enhancing detection accuracy through regression analysis of time-frequency and surface wave data. The consistency between theoretical models and experimental results was further validated by Brancheriau *et al.* by employing modal analysis to investigate the impact of structural irregularities on the frequency characteristics of xylophone bars during tuning (Brancheriau *et al.* 2005). At the onset of the 21st century, vibrational analysis was integrated with neural network technology by Dackermann *et al.* (2008) to develop an innovative method for damage identification in wooden structures, enabling precise localization and severity assessment of damage and demonstrating the potential of artificial intelligence in wood defect detection. In 2014, modal testing was conducted by Samali *et al.* on timber beams and bridges to obtain dynamic characteristics, such as intrinsic frequencies, damping ratios, and vibrational modes, thereby providing a substantial dataset for damage identification. Damage location and severity were predicted by utilizing artificial neural networks, which learned from modal test data, further applying artificial intelligence in wood defect detection (Samali *et al.* 2014). In 2015, the impact of localized heterogeneity, such as manually drilled holes, on bending vibration frequency was examined by Mehran Roohnia *et al.*, discovering that the location and orientation of heterogeneity significantly influenced frequency variation. This confirmed that localized heterogeneity in wood can be detected and assessed through vibrational frequency analysis (Roohnia and Brancheriau 2015). A damage index based on unitary modal strain energy was employed by Ghiasi *et al.* (2018), combined with a meta-model to evaluate the MSEBI of structural elements, significantly reducing computation time while maintaining the accuracy of damage severity detection.

Since 2006, the measurement and analysis of wood's dynamic properties have been actively explored and refined by Chinese researchers. More precise assessments of wood quality and internal defect detection have been achieved through the employment of sophisticated techniques and methodologies. A study conducted by Yingying Cui revealed that wood defects, such as knots and holes, significantly lower the dynamic modulus of elasticity, with a progressive decrease observed as the number and size of defects increase These insights have been instrumental in subsequent detection efforts. In the same year, an innovative methodology for damage identification was introduced by Chuanshuang Hu *et al.* that combines modal analysis with statistical algorithms, allowing for the precise determination of damage presence and location through the analysis of changes in modal shapes before and after damage (Hu *et al.* 2006). Additionally, the localization capabilities of the wavelet transform were harnessed to identify and pinpoint damage, presenting a novel approach for accurate wood damage detection (Hu and Afzal 2006). In 2008, the impact of hole defects was further clarified by Huadong Xu and his team using finite element and modal analysis, laying the groundwork for the precise localization of such defects (Xu *et al.* 2008). In 2009, the bending vibration method and modal analysis were utilized by Xiaodong Zhu *et al.* to detect and locate knots in wood. It was found that a combination of wavelet packet decomposition, resonance frequency analysis, and energy rate analysis could effectively identify and position knots (Zhu *et al.* 2009). Throughout the 2010s, advances in the field were continued by Chuanshuang Hu *et al.* by using frequency and vibrational mode data from wood beams to analyze changes in modal flexibility post-damage, thereby pinpointing damage locations (Hu *et al.* 2001). In 2011, a vibrational method was employed by Huadong Xu to detect hole defects in wood, providing insights into how these defects affect the dynamic elastic modulus (Xu and Wang 2011).

In 2011, vibrational modal testing and modal analysis were utilized by Songyuan Ni on wood-plastic composite panels, uncovering that the presence of holes substantially lowered the panels' dynamic elastic modulus (Ni 2011). In 2014, wavelet packet transform was integrated with modal analysis by Zhu *et al.* for the non-destructive detection of bulging defects in poplar veneer laminates, with the location and size of the defects ascertained through wavelet packet energy curvature analysis (Zhu and Liu 2014). In 2016, modal analysis was conducted by Minliang Zhong *et al.* on naturally defective wood, effectively identifying knots and cracks. The study revealed that cracking notably decreased the wood's first-order resonance frequency, disrupting the smoothness of the vibrational curves and the first-order symmetry of the vibrational mode (Zhong 2016; Zhong *et al.* 2016). In 2017, modal analysis was applied by Yue Wei to identify crack damage in the wooden structural beams of historical buildings, highlighting the high utility of curvature modal indices in damage identification (Wei 2017). By 2023, two novel methods for detecting damage in wooden beams based on modal analysis were introduced by Shanzhou Zeng (2023), confirming their effectiveness through finite element simulations and experimental studies.

The evolution of internal defect detection in wood has been significantly enhanced by the integration of traditional modal analysis with advanced artificial intelligence (AI) and machine learning (ML) methodologies. The accuracy and efficiency of defect detection are improved by these cutting-edge technologies, which also provide substantial support for the sustainable utilization of wood resources and the maintenance of structural integrity. As technology continues to advance, the field of wood defect detection is poised to become increasingly intelligent and automated, paving the way for innovative developments within the wood industry.

DEVELOPMENTAL TRENDS OF VIBRATIONAL METHODS

Vibration-based methods are regarded as vital non-destructive testing (NDT) techniques for assessing the intrinsic quality of wood. By analyzing the wood’s response to vibrations, numerous benefits are offered by this method. However, the precision and reliability of vibrational signal analysis can be affected by various factors, including ambient noise, transducer accuracy, and the inherent inhomogeneity of wood. To address these challenges, advanced signal processing methodologies, such as wavelet packet analysis, are being explored by researchers, along with the integration of machine learning and deep learning algorithms. Wavelet packet analysis facilitates the isolation of specific energy components within a signal across multiple frequency bands by applying a wavelet packet transform to the vibrational signals of wood. This technique assists in examining the correlation between these components and the acoustic attributes of wood (Yin *et al.* 2021). The implementation of these advanced signal processing technologies can significantly reduce noise interference, thereby enhancing the accuracy of extracted vibrational signal features and improving the reliability of wood performance assessments. Furthermore, a comprehensive understanding of wood's performance characteristics is provided by the synergy of vibrational and modal analysis, thereby augmenting both the reliability and thoroughness of the detection process.

Harnessing machine learning, particularly deep learning, is seen as a way to open innovative pathways for enhancing the accuracy of vibrational signal analysis in wood property testing. By training models to recognize patterns within vibrational data, increased precision in predicting wood's mechanical properties can be achieved. A study by Fathi *et al.* (2020) demonstrated that the integration of Lamb wave propagation with machine learning algorithms can accurately forecast the modulus of elasticity and the modulus of rupture (flexural strength) of wood, surpassing the accuracy of conventional ultrasonic techniques. Concurrently, advancements in the application of artificial intelligence in the field of fracture mechanics are being made, encompassing crack detection, diagnosis, and predictive modeling, thereby improving both the precision and efficiency of wood property assessment (Ren and Shuai 2023). Moreover, significant potential in detecting wood defects has been shown by deep learning techniques. For instance, a wood surface defect detection system leveraging the YOLOv8 algorithm can accurately identify various defects, such as cracks, knots, and insect infestations. These deep learning models excel at automatically extracting key anatomical features of wood, which are essential for predicting its mechanical properties. Convolutional neural networks (CNNs) are recognized as particularly effective for image recognition tasks, facilitating the detection of wood texture and defects. Similarly, time-series wood data, such as fluctuations in moisture content throughout the drying process, can be analyzed by recurrent neural networks (RNNs) and long short-term memory networks (LSTMs) (Liu *et al.* 2023).

Incorporating machine learning and deep learning into wood performance inspection is seen as a method that not only enhances the accuracy of vibrational signal analysis but also paves the way for innovative methods of wood defect detection. As technology continues to evolve, a significant rise in the adoption of these sophisticated techniques in wood processing and inspection is expected. Concurrently, the development of portable and intelligent wood vibrational inspection devices is recognized as a promising frontier in the field. The growing ubiquity of the Internet of Things (IoT) is facilitating the seamless integration of vibrational testing technology with smart devices, enabling real-time and remote monitoring of wood characteristics. Such advancements are expected to significantly enhance quality control practices throughout the wood production, processing, and utilization stages, thereby bolstering the intelligent and sustainable progression of the wood industry.

CONCLUSIONS

A comprehensive review of the core principles and significant advantages of vibrational methods has been presented in this paper, alongside an in-depth examination of its development and the latest research outcomes in wood property and defect detection. The accuracy and applicability of vibrational methods have been markedly improved by global researchers through the integration of various technologies, including sensor technology, advanced signal processing, Fast Fourier Transform (FFT), modal analysis, and computer-aided simulation. These advancements not only enhance the precision and effectiveness of wood detection techniques but also establish a critical scientific foundation for the efficient use and structural design of wood. Furthermore, a prospective trajectory for the growth of vibrational methods has been outlined in this paper. As sensor technology, signal processing, and computer simulation continue to advance, a significant expansion in the applicability of vibrational methods is expected. Notably, the integration of vibrational methods with machine learning and artificial intelligence is anticipated to propel wood performance testing toward greater intelligence and automation. Ultimately, substantial potential is possessed by vibrational methods to strengthen wood property testing, laying a robust foundation for technological innovation and the sustainable growth of the wood industry.

REFERENCES CITED

Axmon, J., Hansson, M., and Sörnmo, L. (2002). "Modal analysis of living spruce using a combined PRONY and DFT multichannel method for detection of internal decay," *Mechanical Systems and Signal Processing* 16(4), 561-584. DOI: 10.1006/mssp.2002.1491

Axmon, J., Hansson, M., and Sörnmo, L. (2004). "Experimental study on the possibility of detecting internal decay in standing *Picea abies* by blind impact response analysis," *Forestry* 77(3), article 179. DOI: 10.1093/forestry/77.3.179

Beall, F. C. (2000). "Subsurface sensing of properties and defects in wood and wood products," *Subsurface Sensing Technologies & Applications* 1(2), 181-204. DOI: 10.1023/A:1010135009428

Brancheriau, L., Bailleres, H., and Sales, C. (2005). "Acoustic resonance of xylophone bars: Experimental and analytic approaches of frequency shift phenomenon during the tuning operation of xylophone bars," *Wood Science and Technology* 40(2), 94-106. DOI: 10.1007/s00226-005-0011-3

Chen, B. C. (2022). "Application and development directions of non-destructive testing methods for wood," *Electromechanical Technology* 2022(04), 99-101. DOI: 10.19508/j.cnki.1672-4801.2022.04.028.

Chen, L., Han, S., Li, D., Chen, F., and Wang, G. (2022). "The effect of constituent units on the vibration reduction of bamboo engineering materials: The synergistic vibration reduction mechanism of bamboo stiffness and wood damping," *Industrial Crops and Products* 189, article ID 115785. DOI: 10.1016/j.indcrop.2022.115785

Cui, Y. Y. (2006). *Research on Wood Stress Grading and Defect Detection Based on Vibration Method*, Doctoral Dissertation, Beijing Forestry University, Beijing, China.

Dackermann, U., Li, J., Samali, B., Choi, F., and Crews, K. (2008). "Experimental verification of a vibration-based damage identification method in a timber structure utilising neural network ensembles," *Rilem Publications*.

Fathi, H., Nasir, V., and Kazemirad, S. (2020). "Prediction of the mechanical properties of wood using guided wave propagation and machine learning," *Construction and Building Materials* 262, article ID 120848. DOI: 10.1016/j.conbuildmat.2020.120848

Ghiasi, R., Ghasemi, M. R., and Noori, M. (2018). "Comparative studies of metamodeling and AI-Based techniques in damage detection of structures," *Advances in Engineering Software* 125, 101-112. DOI: 10.1016/j.advengsoft.2018.02.006

Green, D. W., Gorman, T. M., Evans, J. W., and Murphy, J. F. (2006). "Mechanical grading of round timber beams," *Journal of Materials in Civil Engineering* 18(1), 1-10. DOI: 10.1061/(ASCE)0899-1561(2006)18:1(1)

Guan, C., Zhou, L. J., Zhang, H. J., and Lin, W. (2016). "Determination of elastic modulus of full-scale wood-based panels by vibration method," *Journal of Zhejiang A&F University* 2016(06), 1067-1072.

Hu, C., and Afzal, M. T. (2006). "A statistical algorithm for comparing mode shapes of vibration testing before and after damage in timbers," *Journal of Wood Science* 52(4), 348-352. DOI: 10.1007/s10086-005-0769-9

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. DOI: 10.1007/s10086-005-0783-y

Hu, C., Xiao, M., Zhou, H., Wen, W., and Yun, H. (2011). "Damage detection of wood beams using the differences in local modal flexibility," *Journal of Wood Science* 57(6), 479-483. DOI: 10.1007/s10086-011-1200-3

Hu, Y. C., Gu, J. Y., and Wang, F. H. (2002). "Development and prospects of non-destructive testing technology for physical and mechanical properties of wood and wood-based panels," *World Forestry Research* 2002(04), 39-46. DOI:10.13348/j.cnki.sjlyyj.2002.04.007

Hu, Y. C., Wang, F. H., Liu, Y. X., and Nakao, T. (2001). "Detection of bending elastic modulus of plywood by vibration method," *Wood Industry* (2), 3-5+8. DOI: CNKI:SUN:MCGY.0.2001-02-000

Hu, Y. C., Wang, F. H., Liu, Y. X., and Nakao, T. (2001). "Detection of shear elastic modulus of plywood by vibration method," *Wood Industry* 2001(04), 12-14. DOI: 10.19455/j.mcgy.2001.04.004

Hua, J., Wang, H. D., Lei, M., Wang, Z. Q., and Jia, N. (2015). "Detection of elastic modulus of specification timber based on eccentric pressure roller mechanical stress grading method," *Journal of Northeast Forestry University* (12),74-77. DOI: 10.13759/j.cnki.dlxb.20151116.015

Jaramillo, P., Manarky, K. S., Adrezin, R. S., Celmer, R. D., and Shety, D. (2003). "Sweet spot or sweet zone? Modal analysis of a wooden baseball bat for design optimization," in: *ASME 2003 International Mechanical Engineering Congress and Exposition*, Washington, DC, USA, pp. 1019-1025. DOI: 10.1115/IMECE2003-41924

Liu, B. L., and Han, E. Z. (1991). "Experimental modal analysis of piano soundboard vibration," *Musical Instruments* 1991(03), 8-12. DOI:CNKI:SUN:YIQI.0.1991-03-004

Liu, B. L., and Liu, D. J. (1991). "Dynamic elastic modulus of wood and its determination," *Musical Instruments* 1991(04), 6-8. DOI:CNKI:SUN:YIQI.0.1991-04-002

Liu, M. (2014). "Multi-angle interpretation of the eighth national forest resource survey results," *Forestry Economics* (05), 3-9+15. DOI: 10.13843/j.cnki.lyjj.2014.05.001

Liu, Y., Zhuang, Z. L., and Tang, M. (2023). "Research progress of deep learning in the field of timber processing," *Forestry Engineering Journal* 8(4), 1-9. DOI: 10.13360/j.issn.2096-1359.202211004

Ni, S. Y. (2011). *Research and Defect Identification of Vibration Characteristics of Wood-Plastic Composite Boards Based on Modal Analysis*, Doctoral Dissertation, Northeast Forestry University, Haerbin, China.

Niu, S. G., and Chen, L. (2014). "Brief analysis of the impact of wood defects on material quality," *Heilongjiang Science and Technology Information* 2014(04), article 252.

Olaoye, K., and Okon-Akan, O. A. (2020). "Estimation of modulus of elasticity of *Boscia angustifolia* wood using longitudinal vibration acoustic method," *International Wood Products Journal* 11(3), 122-128. DOI: 10.1080/20426445.2020.1738118

Qi, L., Zhang, L., Zhao, M., and Chui, Y. (2023). "Low-cost design of vibration inspection equipment for timber beam," *Journal of Vibration Engineering & Technologies* 12, 481-493. DOI: 10.1007/s42417-023-00854-3

Ren, W., and Shuai, J. (2023). "Application of artificial intelligence in fracture mechanics—crack identification, diagnosis, and prediction," *Mechanics in Practice* 45(01), 1-9.

Roohnia, M., and Brancheriau, L. (2015). "Orientation and position effects of a local heterogeneity on flexural vibration frequencies in wooden beams," *CERNE* 21(2), 339-344.

Ross, R. J., and Pellerin, R. F. (1991). "Nondestructive evaluation of wood—past, present, and future," in: *Nondestructive Characterizations of Materials IV*, C. O. Ruud, J. F. Bussière, and R. E. Green (eds.), Springer, New York, NY, USA, pp. 59-64. DOI: 10.1007/978-1-4899-0670-0_8

Samali, B., Li, J., Dackermann, U., and Choi, F. C. (2014). "Vibration-based damage detection for timber structures in Australia," *Structural Health Monitoring in Australia* 2021, 81-108.

Shi, B. Z., Ruan, X. R., and Wu, D. Z. (1989). "Comparison of several methods for measuring elastic modulus and internal friction of wood," *Journal of Nanjing Forestry University (Natural Science Edition)* 13(04), 21-28.

Sobue, N. (1988). "Simultaneous determination of Young's modulus and shear modulus of structural lumber by complex vibrations of bending and twisting," *Journal of the Japan Wood Research Society* 8(4), 561-573. DOI: 10.1080/02773818808070701

Tao, Y. P., Lin, Y., Shi, J. Y., Tang, S. Y., Jiang, Y. H., and Xu, B. H. (2023). "Study on quality grading of wood elastic modulus based on visual and vibration methods," *Woodworking Machinery* (03), 1-5.

Teixeira, D. E. (2016). "Evaluation of maximum strength and modulus of elasticity of Douglas-fir lumber in axial to grain tension by two nondestructive techniques," *Brazilian Journal of Wood Science* 7(1), 1-6. DOI:10.12953/2177-6830/rcm.v7n1p1-6

Wang, C. Z. (2007). *Vibration-Based Detection System for Wood-Based Panels: Research and Application*, Doctoral Dissertation, Beijing Forestry University, Beijing, China.

Wang, J. J., Xia, D. Y., and Chen, X. (2015). "Study on the method of testing the elastic modulus of glued timber beams by vibration method," *Journal of Central South University of Forestry and Technology* 35(4), 105-108. DOI: 10.14067/j.cnki.1673-923x.2015.04.018

Wang, L. H., Yang, X. C., and Xu, K. H. (2002). "Current status of non-destructive detection technology for wood defects," *Forestry Science and Technology* 27(03), 35-38.

Wang, S. Y., Wang, S. A., Ding, Y. W., Liu, J. Y., and Che, Z. Y. (1994). "Brief discussion on the impact of wood defects on material quality and properties," *Forestry Science and Technology Information* (2), 1-3.

Wang, X., Wacker, J. P., Ross, R. J., and Brashaw, B. K. (2005). "Nondestructive assessment of timber bridges using a vibration-based method," *American Society of Civil Engineers* 2005, 1-12. DOI: 10.1061/40753(171)39

Wang, Z. (2007). "Dynamic measurement of elastic modulus and damping ratio of two types of wood-based composite materials," *Journal of Nanjing Forestry University: Natural Science Edition* 2007(03), 147-149.

Wang, Z., Dai, Y. H., Hong, Z., and Hao, J. D. (2010). "Measurement and analysis of dynamic damping ratio characteristics of PE-based wood-plastic composites," *Woodworking Machinery* (01), 18-20.

Wang, Z., Rao, X., Yang, X. J., Liang, X. Y., and Yang, J. (2013). "Non-destructive detection and grading of elastic modulus of light wood structure specification timber using two methods," *Forest Products Industry* 2013(05), 30-33. DOI: 10.19531/j.issn1001-5299.2013.05.011

Wang, Z., Zhou, J. Y., Zhou, T., Hong, L. J., and Tong, F. L. (2010). "Dynamic measurement of elastic modulus of PE-based wood-plastic composites," *Forestry Machinery and Woodworking Equipment* 2010(6), 3. DOI: CNKI:SUN:LJMG.0.2010-06-007

Wei, Y. (2017). *Research on Damage Identification of Cracks in Ancient Building Timber Structures*, Doctoral Dissertation, Beijing University of Civil Engineering and Architecture, Beijing, China. DOI: CNKI:CDMD:2.1017.169787

Xia, D. Y. (2015). *Research on the Testing Method of Elastic Modulus of Glued Timber Based on Vibration Method*, Doctoral Dissertation, Central South University of Forestry, Changsha, China.

Xie, Z., Hu, X., Du, H., and Zhang, X. (2020). "Vibration behavior of timber-concrete composite floors under human-induced excitation," *Journal of Building Engineering* 32, article ID 101744. DOI: 10.1016/j.jobe.2020.101744

Xiong, H. B., Long, Y. W., Chen, L., and Ding, Y. W. (2023). "Non-destructive testing technology research and application summary of timber structures," *Structural Engineer* 39(1), 191-201. DOI: 10.15935/j.cnki.jggcs.2023.01.011

Xu, H. D., and Wang, L. H. (2011). "The influence of local defects on the dynamic elastic modulus of wooden beams," *Journal of Building Materials* 2011(05), 653-658.

Xu, H. D., Wang, L. H., and Ni, S. Y. (2008). "Quantitative detection of hole defects in wooden specimens based on curvature modal," *Journal of Northeast Forestry University* (11), 9-10+24.

Yang, X., Amano, T., Ishimaru, Y., and Iida, I. (2003). "Application of modal analysis by transfer function to nondestructive testing of wood II: Modulus of elasticity evaluation of sections of differing quality in a wooden beam by the curvature of the flexural vibration wave," *Journal of Wood Science* 49(2), 140-144. DOI: 10.1007/s100860300022

Yang, X., Ishimaru, Y., Iida, I., and Urakami, H. (2002). "Application of modal analysis by transfer function to nondestructive testing of wood I: Determination of localized defects in wood by the shape of the flexural vibration wave," *Journal of Wood Science* 48(4), 283-288. DOI: 10.1007/BF00831348

Yang, Y., and Shen, S. J. (2010). "Research history, current status and prospects of wood non-destructive testing technology," *Science and Technology Guide* 2010(14), 113-117.

Yin, Y. X., Miao, Y. Y., Wan, K., Wang, X. Y., Zhai, X. Y., and Liu, Z. B. (2021). "Analysis and evaluation of wood acoustic vibration signals based on Daubechies wavelet basis," *Forestry Engineering Journal* 006(005), 68-75. DOI: 10.13360/j.issn.2096-1359.202012016

Zeng, S. Z. (2023). *Research on Wood Beam Damage Detection Technology Based on Modal Analysis and Stress Wave*, Doctoral Dissertation, Nanjing Forestry University, Nanjing, China. DOI: 10.27242/d.cnki.gnjlu.2023.001015

Zhang, H. J., Cui, Y. Y., Wang, C. Z., Fu, F., and Su, J. (2009). "Measuring the elastic modulus of structural timber using transverse vibration method," *Forestry Practical Technology* 000(012), 57-59. DOI: CNKI:SUN:LYKT.0.2009-12-034

Zhenbo, L., Yixing, L., Haipeng, Y. U., and Junqi, Y. (2006). "Measurement of the dynamic modulus of elasticity of wood panels," *Frontiers of Forestry in China* 1, 425-430.

Zhong, M. L. (2016). *Non-Destructive Detection of Wood Defect Location Based on Modal Analysis*, Doctoral Dissertation, Northeast Forestry Univ., Haerbin, China.

Zhong, M. L., Qin, L. L., and Liu, Z. B. (2016). "The impact of crack defects on the vibration performance of wood," *J. Northwest Forestry Univ.*2016(05), 261-266.

Zhou, J., Chui, Y. H., Gong, M., and Hu, L. (2016). "Simultaneous measurement of elastic constants of full-size engineered wood-based panels by modal testing," *Holzforschung* 70(7), 673-682. DOI: 10.1515/hf-2015-0117

Zhou, J., Chui, Y. H., Gong, M., and Hu, L. (2017). "Comparative study on measurement of elastic constants of wood-based panels using modal testing: Choice of boundary conditions and calculation methods," *Journal of Wood Science* 63(5), 1-16. DOI: 10.1007/s10086-017-1645-0

Zhou, Z. R., Zhao, M. C., and Wang, Z. (2014). "Comparison of three methods for measuring the elastic modulus of poplar wood," *Journal of Fujian Forestry Science and Technology* 2014(04), 368-373. DOI: 10.13324/j.cnki.jfcf.2014.04.030

Zhu, X. D., Cao, J., Wang, F. H., and Sun, J. P. (2009). "Non-destructive detection of knot location in larch based on vibration modal analysis," *Scientia Silvae Sinicae* 45(5), 169-172.

Zhu, X. D., and Liu, Y. (2014). "Detection and location of defects in laminated veneer lumber by wavelet package analysis," *BioResources* 9(3), 4834-4843. DOI: 10.15376/biores.9.3.4834-4843

Zhu, X. D., Wang, F. H., Cao, J., and Sun, J. P. (2010). "Study on a non-destructive testing system for wood vibration based on virtual instruments," *Journal of Northwest Forestry University* 25(5), article 39. DOI: CNKI:SUN:XBLX.0.2010-05-039

Article submitted: November 26, 2024; Peer review completed: March 1, 2025; Revised version received and accepted: March 5, 2025; Published: March 13, 2025.
DOI: 10.15376/biores.20.2.Shi