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A wavelet analysis-based approach for damage localization in wood beams

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Abstract Free vibration testing was conducted to generate the first two mode shapes for damage detection in timbers. A wavelet transform was proposed to postprocess the mode shapes for damage pattern recognition. The wavelet used here was "db3." The different damage severities, damage locations, and number of damaged areas were simulated by removing mass from intact beams. The results showed that the chosen wavelet db3 is suitable and that the wavelet coefficients are sufficiently sensitive to identify the existence of damage and its location in cases of different damage location, severity, and number. An edge distortion effect was apparent at the two computing edges where the wavelet coefficients were abnormally high. The wavelet coefficients showed dominant spikes around the damage locations and were zero everywhere else except the two computing edges. The dominant spikes coincided well with the damage location.

Key words Damage detection · Wavelet analysis · Wood beam · Nondestructive test

Introduction

Timbers are susceptible to fungal decay and crack development during their service life due to mechanical and environmental loadings, which are different from initial local disturbances due to knots. Such local damage results in reduction of system performance, structural safety, and integrity. It is very critical to monitor the weakest location and detect damage at the earliest possible stage to avoid future catastrophic fracture in most engineering fields. Instances of local damage induce local flexibility, which affects the dynamic behavior of the whole structure. It results in reduction of modal parameters such as natural frequencies, damping, and mode shapes. Some researchers have reported that mode shapes and their derivatives could manifest the local characteristics caused by local disturbances.[1,2] All local and global nondestructive damage-detecting approaches should have two key components; data acquisition and analytical method to extract damage indices.[3] From this point of view, a statistical algorithm for comparing mode shapes of vibration testing before and after damage was proposed to compute the damage indicators in our previous study.[4] The previously proposed algorithm successfully verified the different simulated scenarios of damage locations, different damage severities, and multiple damage points. However, the main drawback is that some prior knowledge is necessary. From the industry application point of view, it is certainly advantageous to develop a damage identification method that does not rely on any prior knowledge of the structure undergoing monitoring.

More recently, the wavelet transform (WT) is emerging as a promising and powerful damage-detecting tool. It has advantages for the detection of localized abnormalities caused by the presence of damage. It has powerful localization characteristics and does not require the prior known mode shapes of intact structure. When compared with Fourier transform, its main advantage is the fact that the local features in a signal can be identified with a desired resolution. The WT is capable of revealing aspects of data that other signal analysis techniques miss, such as transient features, trends, breakdown points, discontinuities in higher derivatives, and self-similarity.[5] The WT has been applied to analyze the cutting noise in circular sawing of particleboards[6] and tapping tone of wood with a knot for the evaluation of wood quality.[7]

In this study, the WT is proposed to analyze spatially distributed signals (mode shapes) of the timber for damage detection. This method was evaluated by different damage scenarios; different damage locations, different damage size, and different quantities.

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Materials and methods

Six uniform and clear beams without any defects after visual grading were cut from a log of white oak (*Quercus rubra*) and their moisture contents were conditioned to around 12%. The beam dimensions were 1200 × 25.4 × 50.8mm. The damage scenarios were simulated by removing mass from the intact beams. The different damage scenarios are listed in Table 1. The schematic diagram of the measuring system is shown in Fig. 1. It consisted of an impact hammer, an accelerometer, two preamplifiers, and a dual-channel fast Fourier transform (FFT) analyzer. Each beam was free–free supported.[8] The material between the supporting points was subdivided into 45 small equal block elements by 44 impacting points and was impacted by the hammer point by point and the resonant signal was picked up by the accelerometer, which was fixed at one of the free ends. Both the output signal from the hammer and the accelerometer were amplified by preamplifiers and were recorded simultaneously using the dual-channel the FFT analyzer. Then the data were dumped from the FFT analyzer to personal computer for damage identification. The analytical software for damage identification was developed in MatLab program language by the authors.

Table 1. Simulated damage scenarios

Scenarios	*w* (mm)	*l*/*L* (%)	*h*/*H* (%)
Case 1 (beam 1)	3	40	5
Case 2 (beam 1)	3	40	10
Case 3 (beam 1)	3	40	20
Case 4 (beam 1)	3	40	40
Case 5 (beam 2)	3	25	20
Case 6 (beam 3)	3	40	20
Case 7 (beam 4)	3	55	20
Case 8 (beam 5)	3	70	20
Case 9 (beam 6)	3	40	20
(beam 6)	3	70	20

See Fig. 1 for definition of sample dimensions *w*, *l*, *L*, *h*, *H*
The mass was removed along the whole width of the sample (25.4mm)

Wavelet transform is usually used to analyze signals in the time domain. However, by replacing the time variable t with a spatial coordinate, spatially distributed signals, i.e., mode shapes, can be analyzed by the WT. In our study, the discrete wavelet transform (DWT) shown as follows was used on the mode shapes.

$$W_{\psi}(a,b)=\int_{\beta 1}^{\beta 2} W_n(\beta)\overline{\psi}_{a,b}(\beta)d\beta,\ a=2^{-j} \tag{1}$$

where β_1 and β_2 are spatial coordinates, n is discrete time, ψ is the wavelet, a is the scale index, b is the shift position index, and j is the level (an integer).

The procedures of this damage detection are described as follows:

1. Generate the mode shapes of the timber by means of impact vibration experiments.
2. Interpolating and wavelet transform of the mode shapes.
3. Plot the wavelet coefficients.
4. Examine the distributions of the wavelet coefficients at each level; a peak or sudden change in the distributions of the wavelet coefficients indicates the damage position or geometric discontinuity.

Results and discussion

The WT is capable of revealing discontinuities of time or space signal.[5] However, the wavelet transform results be-

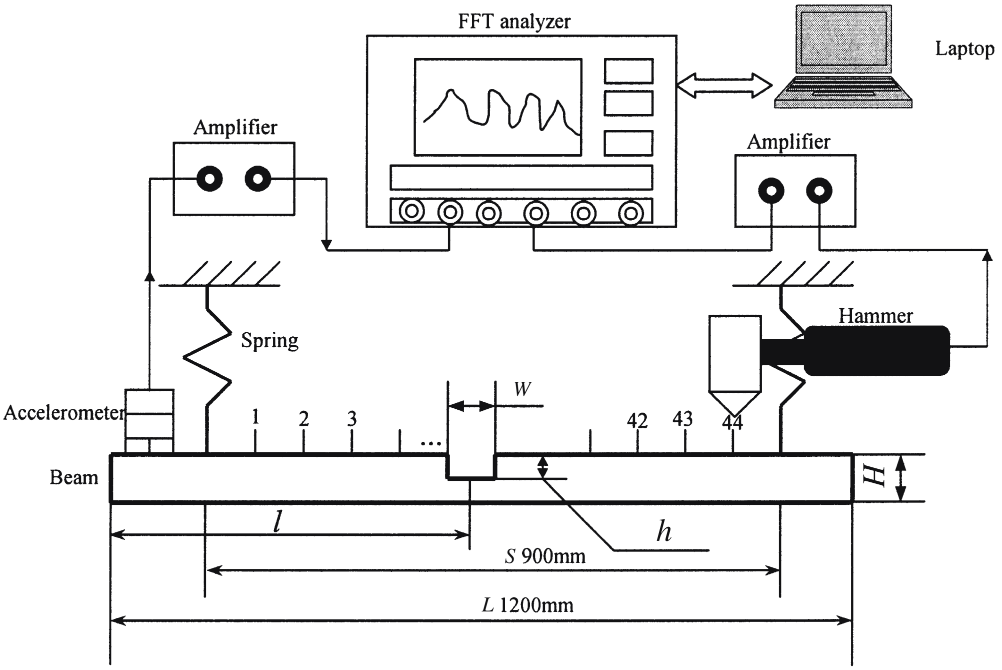

Fig. 1. Diagram of the measuring system

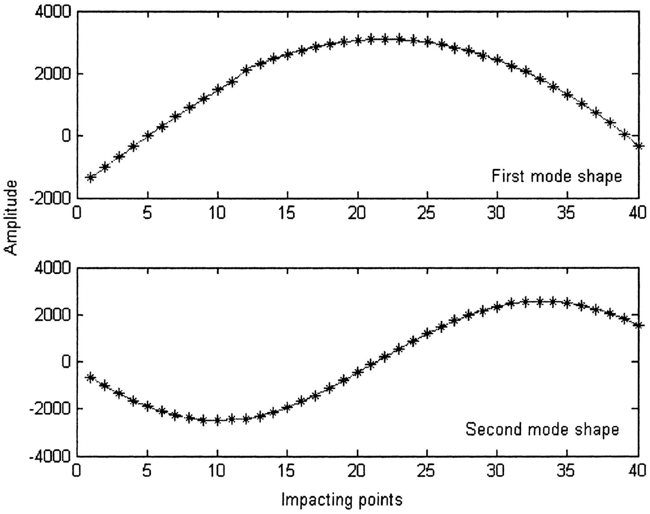

Fig. 2. The first two mode shapes before and after interpolation. *Asterisks*, original data points; *short dashes*, interpolated data points

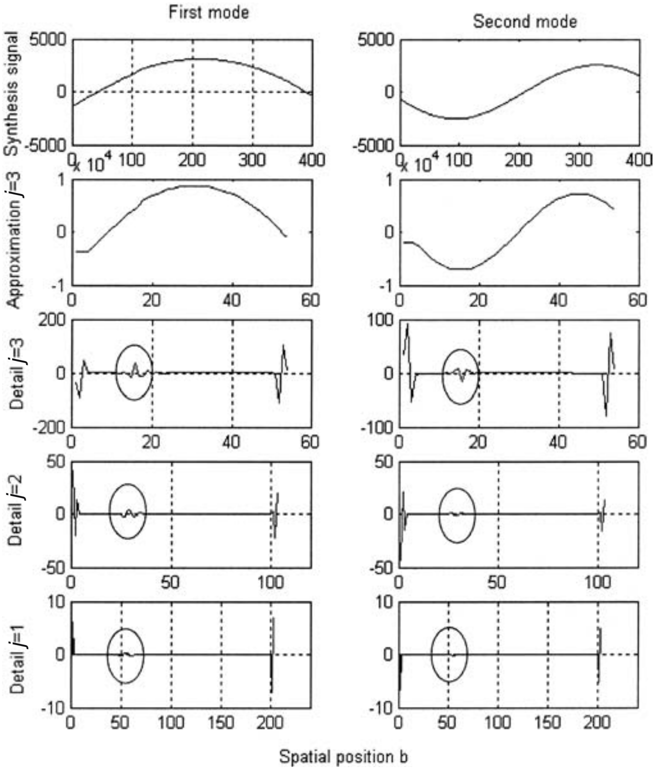

Fig. 3. Plots of approximation and details of the discrete wavelet transform for scenario case 4

come very noisy with sparse data points. The parameter options of the WT depend on the number of data points. Considering the time to generate mode shapes, only impact points from 1 to 40 were conducted and sampled. In order to overcome the lack of data points for the WT, a cubic spline algorithm was used to interpolate data points. The first two mode shapes of scenario case 3 before and after interpolation are shown in Fig. 2. Between two close neighbor interpolated data points, another nine additional data points were interpolated. It is clearly observed that the interpolation smoothes the original signal but does not change its tendency.

The plot of the approximation at level 3 and details (level $j = 1,2,3$) of the DWT for scenario case 4 are shown in Fig. 3. The left and right columns are the graphic displays of the first and second mode, respectively. The first row is the synthesized signal (the approximation at level 3 plus the summation of all the details) and the second row is the approximation at level 3. The last three rows are the details at three different levels. Here the wavelet “db3” was chosen. Considering the computing efficiency, the DWT was used instead of the continuous wavelet transform (CWT). It is easy to reconstruct the original signal by using DWT decomposition as well. Dyadic scales and shift positions, i.e., scales and positions based on powers of two are employed. Therefore, with increasing decomposition levels, the signal scale (data points) decreases. It can be clearly seen that the data points are around half at level 1, one quarter at level 2, and one eighth at level 3 comparing the interpolated data points. This also explains why interpolation was necessary to operate the DWT successfully. Both the approximation and the details show that there is a computing edge distortion of the wavelet analysis. Two dominant peaks appeared in the details and the approximations also stray from the original signals in the left and right edges. This edge distortion will have some impact on damage detection when the damage is close to the computing edge. The edge distortion becomes serious with an increase of the decomposition level. However, the damage was well detected by the DWT with db3: the details are high only close to the damage location (marked by a circle), and are zero everywhere else except the two computing edges. The wavelet coefficients around the damage vary with the decomposition levels. The higher the decomposition levels, the bigger the wavelet coefficients. Considering the computing efficiency and edge distortion, the detail at level 3 is thought to be the optimum level for use as a damage indicator.

The different damage severities (cases 1–4) were simulated to study the effects of the damage severity on the sensitivity of the proposed damage detection method. The plots of wavelet coefficients versus spatial position and damage severity at first and second modes are shown in Figs. 4 and 5. It is apparent that the damage can be located by the wavelet coefficients computed from the first mode shape or the second mode shape. The wavelet coefficients appear to have dominant spikes around the damage locations and are zero everywhere else except the two computing edges. It is reasonable to conclude that the wavelet coefficients are sufficiently sensitive to identify the existence of damage and its location under different damage severities. It is also observed that the wavelet coefficients increase when the damage severity increases. From this point of view, it is reasonable to assume that the wavelet coefficients can be used to qualitatively evaluate the dam-

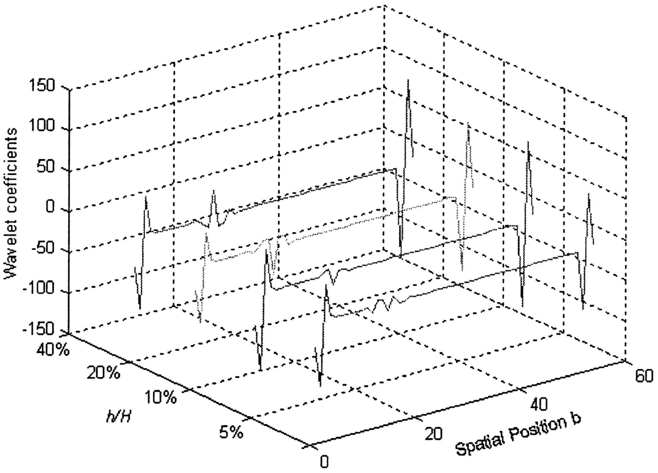

Fig. 4. Plots of wavelet coefficients versus spatial position and damage severity (first mode)

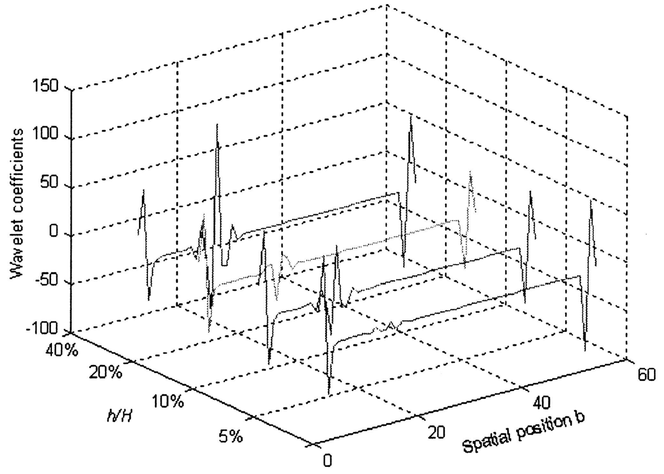

Fig. 5. Plots of wavelet coefficients versus spatial position and damage severity (second mode)

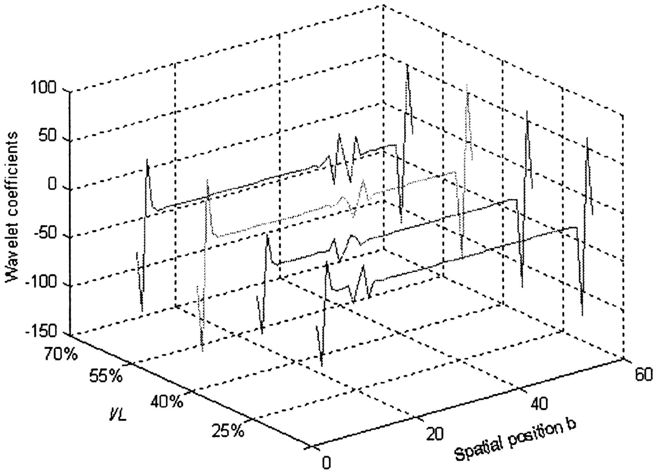

Fig. 6. Plots of wavelet coefficients versus spatial position and damage location (first mode)

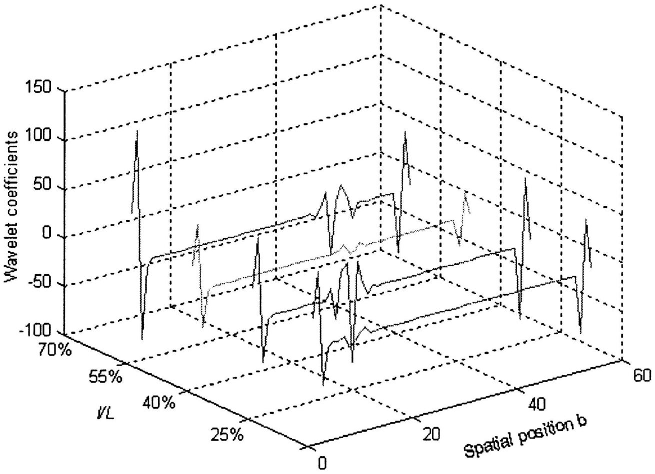

Fig. 7. Plots of wavelet coefficients versus spatial position and damage location (second mode)

age severity as well. However, further studies should be conducted to extract some certain indicators from the WT so that the damage severity and the remaining useful life of the structures can be estimated.

Different damage locations (cases 5–8) were also simulated to study the effects of the boundary conditions and sensor mounting on the effectiveness of the proposed damage detection method. The plots of wavelet coefficients of the first and second modes versus spatial position and damage location are shown in Figs. 6 and 7, respectively. Generally, it appears that the cases of simulated damage at different locations along the beam were correctly detected and located by the wavelet coefficients. The peaks of the wavelet coefficients coincided with the designed damage locations well and the existence of damage and its location could be readily distinguished by the spikes. In our earlier work, it was found that the damage indicators, which were computed by means of a statistical algorithm, were sensitive to the different damage locations and different modal orders.[4] However, the wavelet coefficients do not clearly reflect the effects. It is found that the wavelet coefficients do not appear abnormal when the damage is located at 25% (l/L; see Fig. 1) on the first mode. It should be noted that only the edge distortion will limit the effectiveness when the damage location is very close to the computing edges.

Instances of two areas of damage (case 9) were simulated to verify the effectiveness of the proposed damage detection method. Plots of the wavelet coefficients computed from the first two mode shapes versus spatial position for cases of two areas of damage are shown in Fig. 8. The two areas of damage were detected well. There was no interaction between the damaged areas because mode shape is a much more of a local phenomenon than a global phenomenon and the wavelet transform is capable of detecting two close local discontinuities.

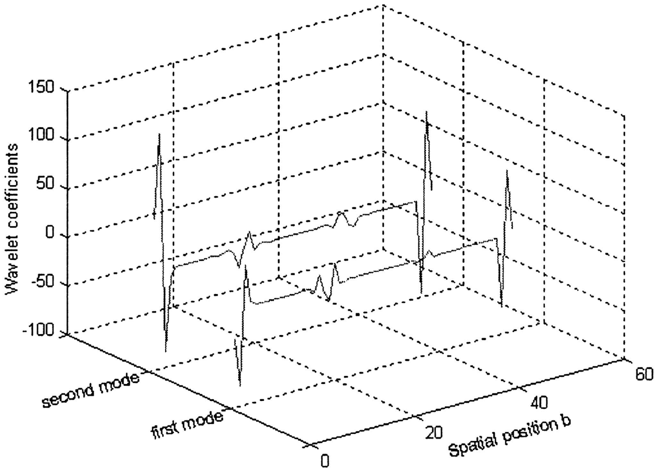

Fig. 8. Plots of wavelet coefficients versus spatial position for specimen with two damage areas

Conclusions

The discrete wavelet transform (DWT) using wavelet db3 was proposed as a means of damage detection in timbers. Different damage severities, damage locations, and number of damage points were simulated by removing mass from intact beams to verify the approach. The results showed that the proposed method is effective and feasible for the intended damage scenarios. The wavelet transform is a reliable means of detection of cases of local damage under of different severity, location, and number without prior known knowledge of the intact beam.

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