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Structural damage identification using signal processing method

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Abstract

The objective of the current work is to show the effectiveness of using wavelet transform for detection and localization of small damages. The spatial data used here are the rotational mode shapes of the damaged and undamaged plate-like structures. The continuous wavelet transform using complex Gaussian wavelet is used to get the spatially distributed wavelet coefficients so as to identify the damage position on a square plate. The rotational mode shape data of the square plate with damage of different sizes are obtained using ANSYS 9.0. Damage identification for different boundary conditions is studied.

Keywords: Damage identification, Gaussian wavelet, Structural damage, Mode shapes, Wavelets

Introduction

Damage in a mechanical (or) structural system may be contributed by various factors, such as excessive response, accumulative crack growth, wear and tear of working parts, and impact by a foreign object. Structural health monitoring has emerged as a reliable, efficient, and economical approach to monitor system performance, detect such damage, asses/diagnose structural health condition, and make corresponding maintenance decisions; consequently, structural safety and functionality will be significantly improved and a condition-based maintenance procedure can be developed. Due to localization of damage in structure techniques using global averaging procedures, changes in eigen frequencies are less sensitive to initial or small changes. Hence, techniques that process the local information based on wavelets have emerged recently. An application of spatial wavelet theory to damage identification in structures was proposed by Liew and Wang (1998). They calculated the wavelet coefficients along the length of the beam based on the numerical solution for the deflection of the beam; the damage location was then indicated by a peak in the coefficients of the wavelets along the length of the beam. Wang and Deng (1999) described a method for detecting the location of localized defects. Quek et al. (2001) also used wavelet analysis for crack identification in beams under both simply supported and fixed-fixed boundary conditions. Hong et al. (2002) used the Lipschitz exponent for the detection of singularities in beam modal data. The Mexican hat wavelet was used, and the damage extent has been related to different values of the exponent. The correlation, however, of the damage extent to the Lipschitz exponent is sensitive to both sampling distance and noise, resulting in limited accuracy of the prediction. Recently, an interesting comparison between a frequency-based and mode shape-based method for damage identification in beam-like structure has been published by Kim et al. (2003). Later, Chang and Chen (2004) used spatially distributed signals by Gabor wavelet transform so that the distributions of wavelet coefficients could identify the damage position of a rectangular plate by showing a peak at the position of the damage which was very sensitive to the damage size. Also, Abdo and Hori (2001) made numerical study of the relation between damage characteristics, and changes in the dynamic properties are presented. It was found that the rotation of mode shape has the characteristic of localization at the damaged region even though the displacement modes are not localized.

Despite the extensive studies on vibration analysis of damaged plates, only few effective and practical techniques are found for very small damage identification. In this paper a study is carried out to investigate the influence of using the rotation of mode shapes as an input

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for the wavelets on damage identification for different scenarios of damage for different boundaries.

Methods

Using rotational mode shapes

In this section, further study is carried out to investigate the influence of using the rotation of mode shapes (Abdo and Hori 2001) as an input for the wavelets on damage identification for different scenarios of damage for different boundaries. The plate, whose length and width is equally divided into 25 elements so the simulated model has a total of 625 elements, is used for analysis. Damage is simulated by reducing the thickness of one element at different locations. Four-noded shell element with six degrees of freedom per node (three translations and three rotations ($U_{x,}$, U_y, U_z, θ_x, θ_y, θ_z)) was used. Since the rotation around the Z-axis (θ_z) is very small for thin plates, only rotations around the X-axis (θ_x) and Y-axis (θ_y) are taken into consideration. These two rotations are normalized with respect to the square root of the sum of squares. The maximum slope at any point of a thin plate can be calculated as (Liew and Wang 1998)

$$Maximum \ \ slope = \sqrt{(\theta_x)^2 + (\theta_y)^2}. \quad (1)$$

Thus, for the sake of generality in this study, the following invariant is used for rotation at the *j*th node of the *i*th mode shape.

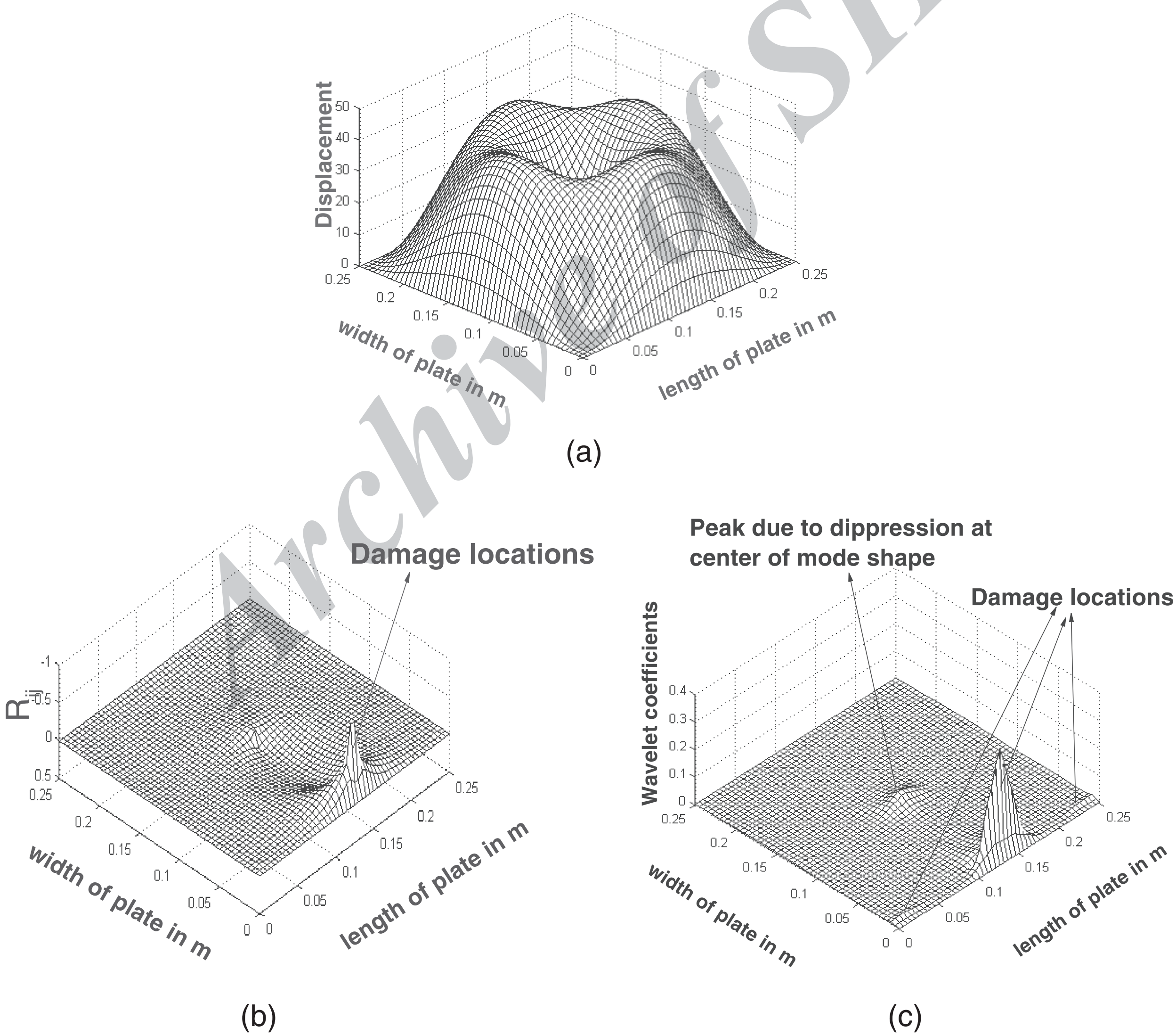

Figure 1 Rotation mode shape of the damaged plate. (**a**) The first rotation mode shape of the (33.33%) damaged plate (boundary conditions are fixed at four edges). (**b**) Absolute difference of the first rotation of mode shapes between the intact and damaged plate. (**c**) The distributions of wavelet coefficients for scale (s = 2) based on the absolute difference of the first rotation of mode shape.

$$R_{ij} = \sqrt{(\theta_x)_{ij}^2 + (\theta_y)_{ij}^2} \qquad (2)$$

The procedure of the damage detection is as follows:

(a) Find the analytical mode shapes of the structure.
(b) Calculate the spatial wavelet coefficients of the mode shapes.
(c) Plot the value of wavelet coefficients in the full region for each scale of wavelets.
(d) Examine the distributions of wavelet coefficients at each scale. A sudden change in the distributions of the wavelet coefficients identifies the damage position.

Results and discussion

All-edges-fixed boundary conditions

In this particular case with a fixed plate, 33.33% severity is introduced (Figure 1a shows the first rotational mode shape of a fixed plate with three damages). Two damages are at the corner of plate, and one is at the center of a particular edge. It is observed from Figure 1b that the damage at the center of the edge is clearly located by high amplitude of absolute difference of the rotation mode shape. The corner damages are not highlighted, as seen in Figure 1b. To increase the sensitivity of the method to identify corner damages, the absolute difference in rotation mode shape is given as input to wavelet transform. The corresponding wavelet coefficient distribution is as shown in Figure 1c. It is clearly observed in

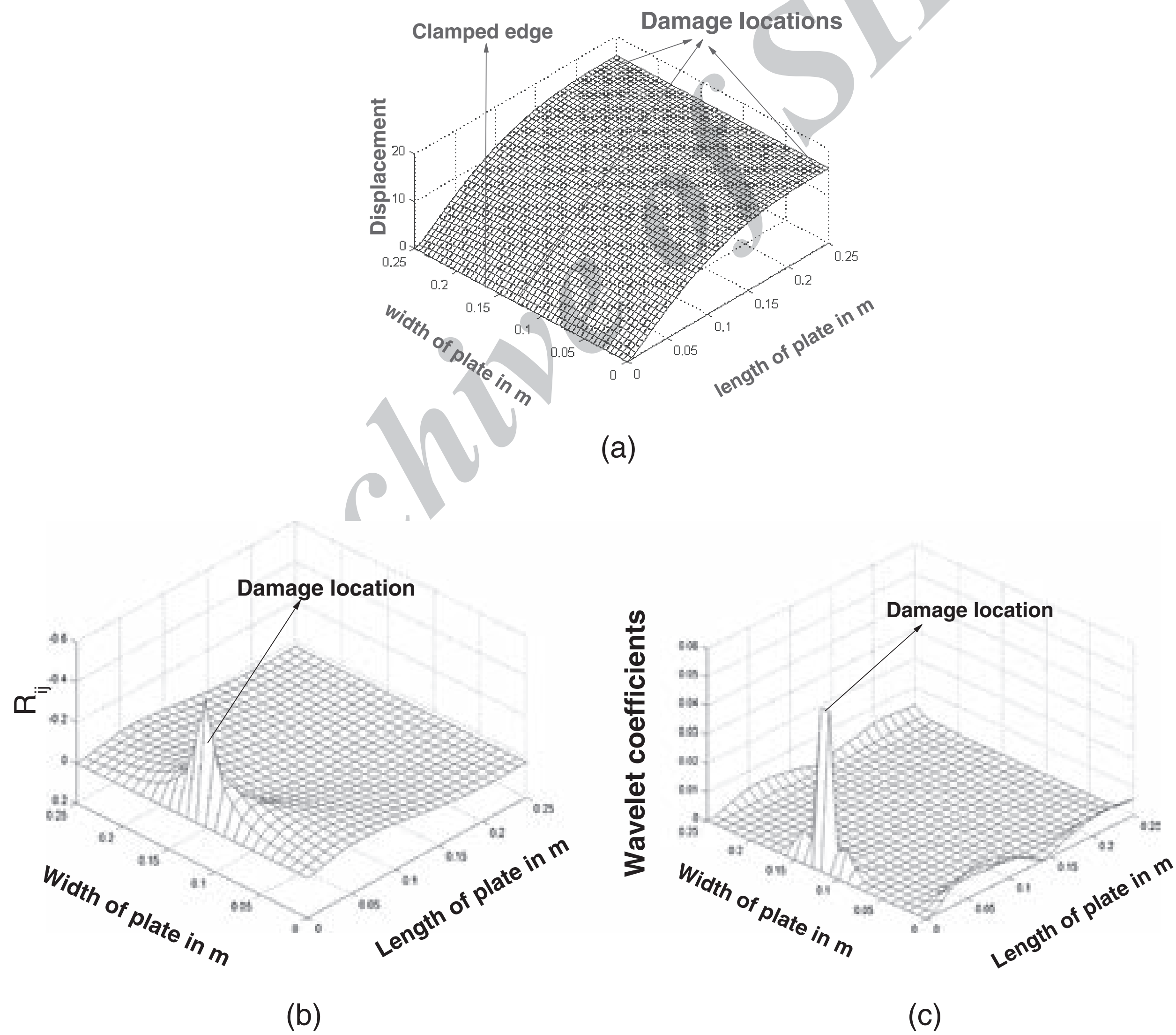

Figure 2 Rotation mode shape of the damaged cantilever plate. (**a**) The first rotation mode shape of the (33.33%) damaged cantilever plate. (**b**) Absolute difference of the first rotation of mode shapes between the intact and damaged plate. (**c**) The distributions of wavelet coefficients for scale (s = 2) based on the absolute difference of the first rotation of mode shape.

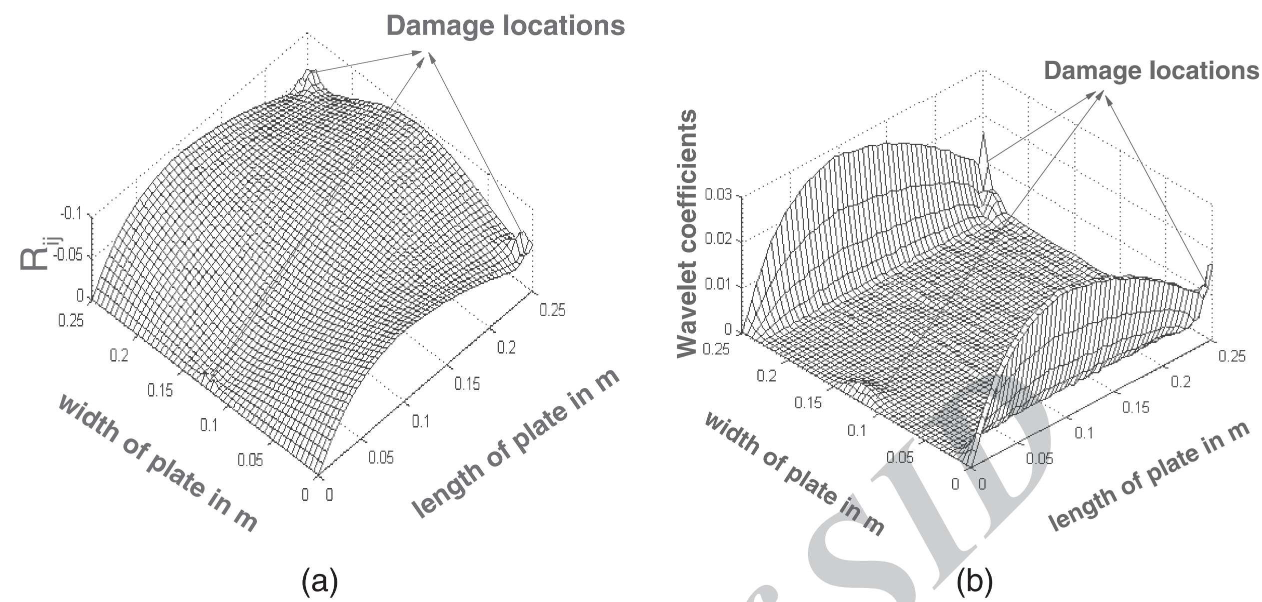

Figure 3 Second rotation of mode shapes. (**a**) Absolute difference of the second rotation of mode shapes between the intact and damaged plates. (**b**) The distributions of wavelet coefficients for scale (s = 2) based on the absolute difference of the second rotation of mode shape.

Figure 1c that the damage at the corner is identified by high coefficients at that location as indicated. Hence, wavelet-transformed rotation mode shape has the potential to identify damages at any locations, which would not be possible by using only rotation mode shape alone. Another observation in Figure 1b,c is that there is a center peak exactly at the center of the plate, which is due to the maximum slope (depression) of the rotation mode shape at the center.

One-edge-fixed boundary conditions (cantilever plate)

The same plate with 33% damage condition is analyzed for a mode shape as a cantilever, as shown in Figure 2a. Two damages are at the free-edge corner of the plate, and one is at the center of plate's clamped edge.

It was observed from Figure 2b that the damage at the center of the clamped edge is clearly located by high amplitude of absolute difference of the first rotation mode shape. However, the two damages at the free-edge corner are not highlighted, as shown in Figure 2b. Further, to increase the sensitivity of the method to identify corner damages, the absolute difference of the first rotation mode shape was inputted to the wavelets. The wavelet coefficient plot as shown in Figure 2c clearly shows which is not sensitive to damages at the free end of the plate.

To find out damages at the free end, absolute difference of the second rotation mode shape is used, as shown in Figure 3a which clearly indicates all three damages. To increase the sensitivity of the method, respective rotation mode shape was inputted to the wavelet. The corresponding wavelet coefficient distribution is as shown in Figure 3b. This clearly identifies the peaks with high wavelet coefficients at damage locations.

Conclusions

The objective of this paper is to apply spatial wavelet transform to highlight the sensitivity for detection and localization of damage in a plate structure with all boundaries fixed, using rotational mode shape as input. It was observed that by using modal data as input, damage can be identified exactly if the reduction in thickness is more than 10%.

Changes in rotations of mode shapes due to the presence of structural damage, represented here in a numerical finite element model, have been investigated. The results of the aluminum plate model demonstrate the usefulness of the changes in the rotation of mode shape as a diagnostic parameter in detecting and locating damage with regard to the plate with different boundary conditions. For identifying damages at a boundary, the method of using absolute difference rotational mode shape data is not sufficient. Thus, boundary damages are best identified when the absolute difference rotation mode shape is given as input to wavelet transform and the coefficients plotted in a length-width plane. It is observed that by using rotation modal data as input, damage can be identified exactly if the reduction in thickness is more than 5%. Below 5% reduction in thickness, absolute difference rotation mode shape data input to wavelet is more sensitive.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
MDR carried out the modeling and wavelet analysis part in Matlab and in CAE softwares. SS carried out the crack detection method for different boundary conditions by taking difference in the healthy and damaged mode shape plate. MDR and SS together analyzed the sensitivity of wavelets to crack detection at different levels of scales. Both authors read and approved the final manuscript.

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