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Mode Shape and Mode Shape Difference Evaluation to Damage Location in Plate Structures

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Abstract

Mode shape is a reliable modal property that provides information regarding the health status of structures. The decomposition of mode shape by using wavelet transform (WT) has provided researchers information needed to identify damage in structures. However, WT decomposition of mode shape differences has shown to provide damage information. In this paper, a comparative study was presented on WT decomposition of mode shape and mode shape difference to detect damage in plate structures. Since reliable higher-order mode shapes can be very difficult to obtain, this study utilized the first mode. Numerical models of square plates with different boundary conditions (one, two and four sides fixed), were applied to evaluate the capabilities of mode shape and mode shape difference to detect damage. Damage was imposed at different locations in the plate models by reducing thickness at such locations. The damage detectability of both methods was analysed and compared when noisy data was applied. The results showed that WT decomposition of mode shape difference was not affected by border distortion, and capable of detecting damage at all locations. However, border distortion problem affected detection of damage at some locations when mode shape was decomposed.

Keywords. Plate; Damage detection; Wavelet transform; Mode shape; Mode shape difference

INTRODUCTION

Exposure of structures to extreme loading and weather conditions increases the existence of damage, thus, increases operational and maintenance costs, and decreases their lifespan. In recent past, maintenance was carried out by visual inspection to detect damage, however, this process is time consuming, cumbersome in large structures and likely impossible in complex ones. Similarly, visual inspection relies solely on the judgment of the inspecting engineer. These drawbacks led to the advent of vibration based damage detection (VBDD) methods to detect damage in structure.

Wavelet transform (WT) is an important tool in extracting information from different types of data [1, 2]. Therefore, WT has been applied by several researchers [3-6] to decompose structural responses of structures to indicate damage characteristics. Mode shape, an important structural response, decomposition by using WT provides information on damage in structures. Mode shape decomposition for damage detection has been reported by several researchers.

Such researches include, Kim et al. [7] investigation of the singularity of a damaged beam both numerically and experimentally by applying discrete wavelet transform on the first fundamental mode shape of the beam. Hong et al. [8] identified damage in beam in terms of Lipschitz exponent by applying Mexican hat wavelet transform to decompose the beam's fundamental mode shape. Later on, Gentile and Messina [9] determined damage characteristics in a beam using continuous wavelet transform (CWT) to analyze vibrational deformation modes. Fan and Qiao [10] detected damage in a plate model by applying a 2-D CWT to decompose the mode shape. The depths and locations of multiple transverse cracks in beam structures were determined by Xiang and Liang [11] using wavelet transform.

In more recent studies, Bai et al. [12] decomposed mode shapes to a set of scale mode shapes by applying stationary wavelet transform so that damage information and noise are separated differently. Amiri et al. [13] utilized the one-dimensional fourth-order B-spline wavelet to identify cracks in a cantilever beam by analyzing the obtained natural vibration modes. Alamdari et al. [14] identified damage in beam structure by using a two-dimensional discrete wavelet transform to analyze the extended operational mode shapes. Gholizad and Safari [15] identified multiple structural damages in space frames by deduction of the coefficients of the two-dimensional (CWT) analyzed fundamental mode shapes of the intact and damaged states.

These studies show the adequacy of mode shape decomposition to detect damage. However, decomposition of mode shape differences have shown to provide damage information [16]. Therefore, this study presents an evaluation of sensitivity of mode shapes and mode shape differences decomposition to damage detection in plate structures. This study provides insight by considering three different plate models by altering the boundaries conditions. Since estimation of higher-order vibration modes is difficult to obtain in real structures, this study utilizes the fundamental mode shape. Numerical models of plates with four sides fixed, two opposite sides fixed, and one side fixed (cantilever) provided in this study. Damage is assumed to result from corrosion and modelled by reducing the thickness of the plates at the points of damage infliction. Similarly, several damage locations are considered in each plate model to evaluate the sensitivity of both methods to damage detection when damage occurs at different points in the plate's models.

In the next sections, the theory of (CWT) is presented, and then the plate models applied in this study are introduced. Next, the wavelet analysis is presented, and results of damage identification are described in details.

CONTINUOUS WAVELET TRANSFORM

The discontinuity introduced in a signal by damage may not be visible to human, but can be detected in wavelet transform coefficients. The mother wavelet function ψ(x) creates a wavelet family ψu,s(x).

$$\psi_{us}(x) = \frac{1}{\sqrt{s}}\psi\frac{(x-u)}{s} \quad (1)$$

where s and u are scale and position respectively.

The CWT of a one-dimensional signal f(x) is as given by Mallat [17] is

$$Wf(u,s) = \frac{1}{\sqrt{s}}\int_{-\infty}^{+\infty} f(x)\,\psi\left(\frac{x-u}{s}\right)dx \quad (2)$$

$Wf(u,s)$ is wavelet coefficient of the wavelet $\psi_{u,s}(x)$.

The two-dimensional CWT of signal f(x, y) is given by Rucka and Wilde [18] as

$$W^i f(u,v,s) = \frac{1}{s}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x)\,\psi^i\left(\frac{(x-u)}{s},\frac{y-v}{s}\right)dxdy$$

$$= \frac{1}{s} f * \psi^i\left(\frac{-u}{s},\frac{-v}{s}\right) = f * \bar{\psi}_s(u,v),\ \ i = 1,2. \quad (3)$$

The horizontal wavelet $\psi^1(x,y)$ and vertical $\psi^2(x,y)$ are constructed with separable products of scaling $\emptyset$ and wavelet function ψ

$$\psi^1(x,y) = \emptyset(x)\psi(y) \quad (4)$$

$$\psi^2(x,y) = \psi(x)\emptyset(y) \quad (5)$$

PLATE NUMERICAL MODELS

Three types of square plate models are applied in this study. Each model has different boundary conditions. The plate models are: plate with four sides fixed, plate with two opposite sited fixed, and plate with one side fixed (cantilever plate). The plates are modeled using finite element software SAP2000 [19], and each model is made up of 784 square thin shell elements of 20 mm by 20 mm. Each plate has a dimension of: length l = 560 mm, width b = 560 mm and thickness h = 2 mm, while the material properties are Poisson's ratio ν = 0.3, Modulus of Elasticity E = 200 Gpa, and mass density ρ = 7850 kg/m^3.

The damage inflicted in each plate model is square of 80 mm by 80 mm dimension. The area of the damage is 2.041% of the plates' area. The plates' boundary conditions and positions of the damage are shown in Figure 1. Table 1 indicates the locations of damage in each plate model. The damage considered in this study is assumed to be caused by corrosion, thus damage is imposed by reducing the thickness of plate at the damage location. The plate's thickness at the location of damage is reduced from 2 mm to 1.5 mm, and with this, a damage severity of 25% is inflicted. A typical cross-section of a plate is showing the imposed damage on the plate is shown in Figure 2. The damage locations in the plates are middle, side, top, corner, free-end and mid-support. Table 1 indicates the locations of damage in each plate model.

Although higher modes are more sensitive to damage, however, in real structures, obtaining these higher modes is difficult to obtain. Similarly, higher modes contain more areas which are not sensitive enough to detect damage, and these areas are called dead zones [20]. Therefore, in this study, the first mode shapes are applied for wavelet transform decomposition. First mode can be easily obtained in practice while it gives a good indication for damage identification. The undamaged first mode of the three plate models are shown in Figure 3. In order to estimate the mode shape difference values, the values at each node in the 1st mode shapes of the damaged plate are subtracted from the values of the undamaged plate. These estimated mode shapes and mode shape differences are normalized to values of between +1 and -1.

WAVELET ANALYSIS FOR DAMAGE DETECTION

The mother wavelet applied to decompose the mode shapes and mode shape differences is Paul wavelet. This is the most appropriate available mother wavelet for damage identification. The basis function of Paul wavelet is shown in Figure 4. Similarly, the scale and angle selected for the decomposition process is important to ensure successful damage identification implementation. Scale and angle indexes selected are 3 and 1 respectively. These parameters are chosen after several thorough trial and errors to select the best combination [21, 22].

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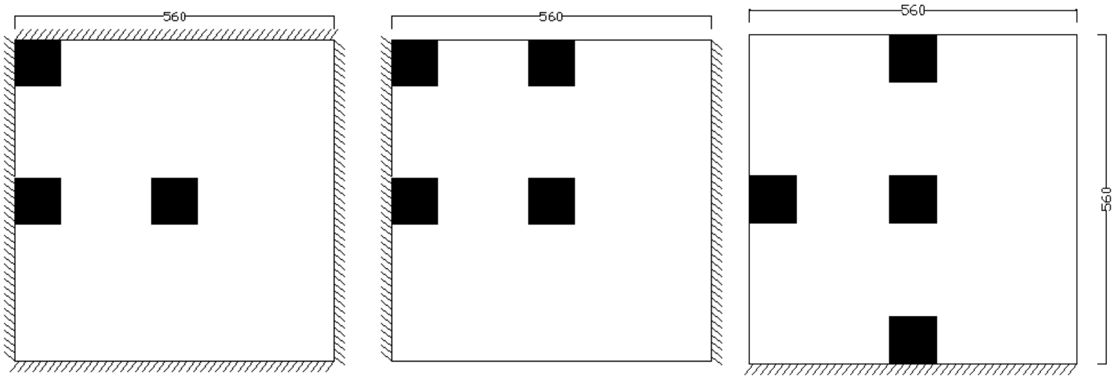


(a) (b) (c)

Figure 1: Square Plate with (a) four sides fixed; (b) Two opposite sides fixed; (c) One side fixed

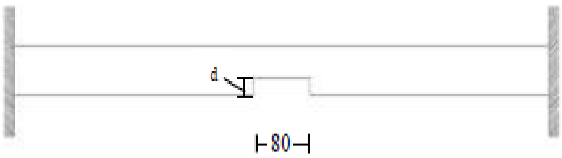
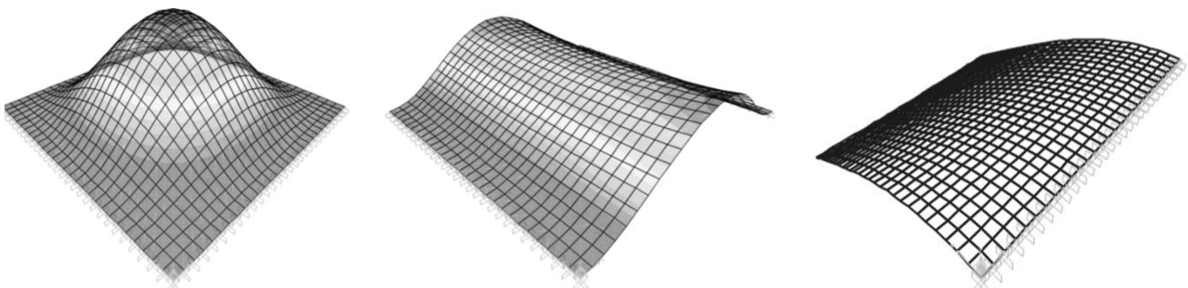


Figure 2: A cross-section showing damage.

Table 1: Damage locations in each plate model

Plate model	Damage locations
Four sides fixed	Middle, corner, side
Two sides fixed	Middle, corner, side, top
One side fixed	Top, mid-support, middle, side



(a) (b) (c)

Figure 3: Undamaged first mode shapes (a) Four sides fixed; (b) Two opposite sides fixed; (c) One side fixed (Cantilever)

The mode shapes and mode shape differences are decomposed by using two-dimensional (CWT) as shown in Equations 4 and 5 for the horizontal and vertical components respectively. The wavelet transform decomposition is done by using Wavelet Toolbox in Matlab R2015a [23], and the position of damage in each model is identified in the wavelet transform coefficients.

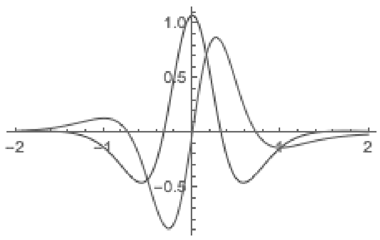


Figure 4: Paul wavelet basis function

DAMAGE DETECTION USING WAVELET ANALYSIS

Plate with four sides fixed

In this section, results of damage detection in the numerical plate model with four side fixed are presented. Figure 5 and Figure 6 show the wavelet coefficients of the decomposed mode shapes and mode shape differences of the plate model respectively. In Figure 5(a) and (c), it can be seen that the middle and side/top damages are accurately detected with no visible border distortion. However, in Figure 5(b), the corner damage is not detected and in addition to this, border distortion and false detections are clearly visible. This shows that the middle and side/top damage effect on the stiffness of the plate submerges the effect of border distortion, but not enough when damage occurs at the corner damage. In Figure 6, the wavelet coefficients of the decomposed mode shape differences are shown. It is clearly seen that effects of border distortion and false damage detection are not visible. The effect of border distortion was eliminated by reducing the stiffness change at the boundaries by applying mode shape differences. The middle corner and side/top damages are accurately detected. The coordinated of the detected middle, corner and side/top damages are (280,280), (40,520), and (40,280) respectively.

Plate with two opposite sides fixed

This section presents the results of the wavelet coefficients of plate model with two opposite sides fixed and free. The wavelet coefficients are shown in Figures 7 and 8 for mode shapes and mode shape differences respectively. Considering the mode shape decomposition results as seen in Figure 7, the corner and top damages in the plate are accurately detected; as shown in Figures 7(b) and (d). Although Figure 7(b) shows the detection of corner damage, effect of border distortion is visible. On the other hand, border distortion is not present in Figure 7(d) due to its submersion by the detected damage that had higher coefficient. In Figures 7(a) and (c), the middle and side damages are not detectable. In addition to this, border distortion is dominant in these coefficients. This indicates that presence of damage at the middle and side locations in the plate do not have enough effect on the plate's stiffness to prompt detection of these damages when the mode shape decomposition is utilized.

In Figure 8, the wavelet coefficients of the plate model using mode shape differences are presented. The four damage locations are accurately detected with neither false damage detection nor effect of border distortion. The resolutions in these coefficients are very good. The absence of border distortion is due to the reduction of sudden change in stiffness experienced at the boundary due to applying mode shape differences. The locations of the detected middle, corner, side and top damages are defined by their coordinates as (280,280), (40,520), (40,280) and (280,520) respectively.

The results in this section show that wavelet transform decomposition of mode shape of this type of plate with this boundary condition is not suitable for damage detection. The absence of border distortion and detection of damage at middle and side locations shows the superiority in using mode shape difference over mode shape in wavelet transform. Thus, application of mode shape differences to detect damage in this type of plate structure is advised.

Plate with one side fixed

Figure 9 and Figure 10 show the wavelet transform coefficients of the mode shape and mode shape difference of the cantilever plate model respectively. As seen in Figure 9(a) to (c), damages located at the top, mid-support and middle of the plate are not detected. The effects of border distortion occur in these coefficients. In Figure 9(d), the side damage is detected correctly in the coefficient, however, the presence of a false damage and border distortion can be seen. This result indicates that wavelet transform decomposition of mode shape for damage detection is suitable when cantilever plate structure is considered.

Figure 10(a) to (d) shows the results of wavelet transform coefficient of mode shape differences of the cantilever plate. From Figure 10(a) to (c), the top, mid-support and middle damages are accurately detected with no signs of border distortion or false detection in the coefficients. The effect of sudden stiffness reduction at the boundary is reduced by applying the mode shape difference, thus, eliminating border distortion. In Figure 10(d), the side damage is detected with no signs of border distortion, however, the presence of false damage detection is seen.

Based on the results in this section, application of mode shape differences provided better results than applying mode shapes. Thus, wavelets transform decomposition of mode shape differences of cantilever plate is more suitable than mode shape for identification of damage.

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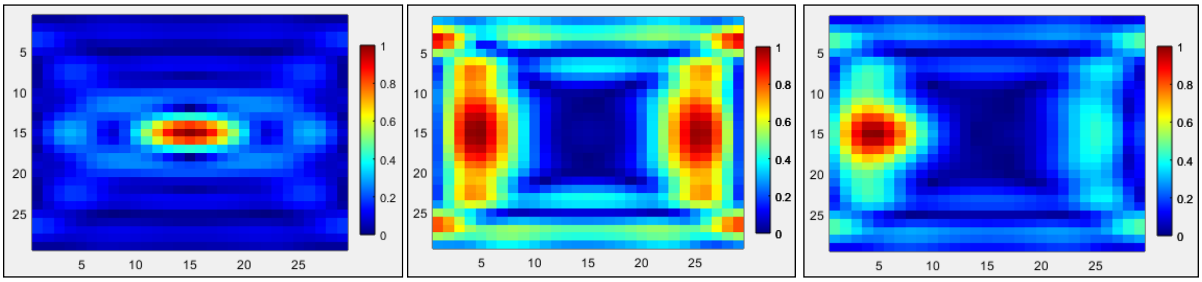
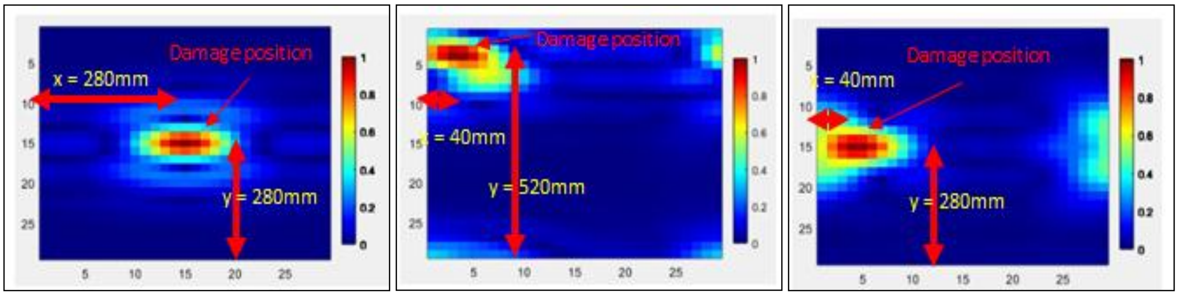


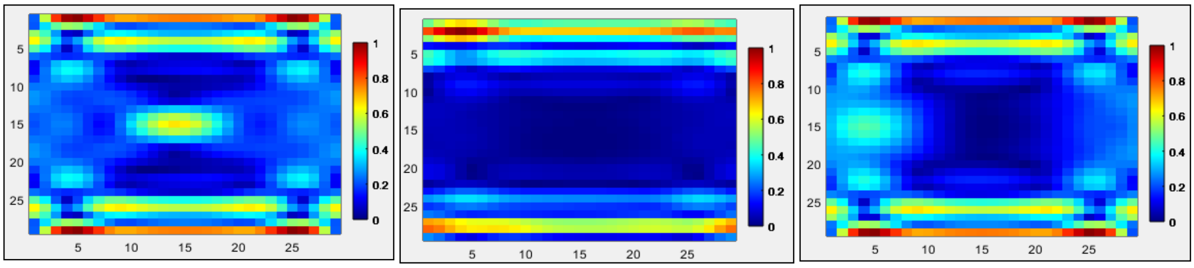
(a) Middle damage (b) Corner damage (c) Side/top damage

Figure 5: Wavelet coefficients of numerical plate model using mode shape (four sides fixed)

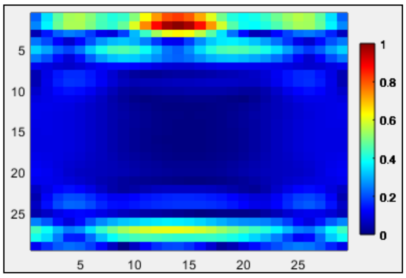


(a) Middle damage (b) Corner damage (c) Side/top damage

Figure 6: Wavelet coefficients of numerical plate model using mode shape difference (four sides fixed)

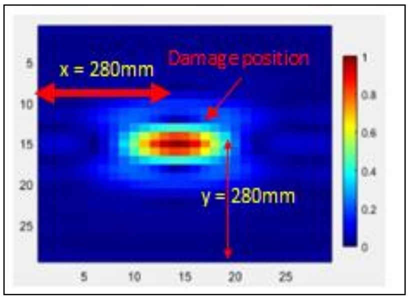


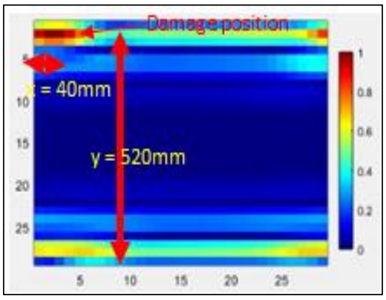
(a) Middle damage (b) Corner damage (c) Side damage

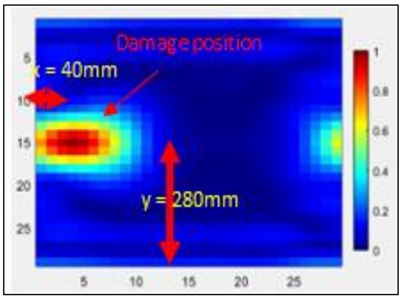


(d) Top damage

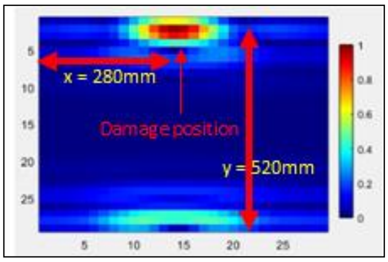
Figure 7: Wavelet coefficients of numerical plate model using mode shape (two opposite sides fixed)





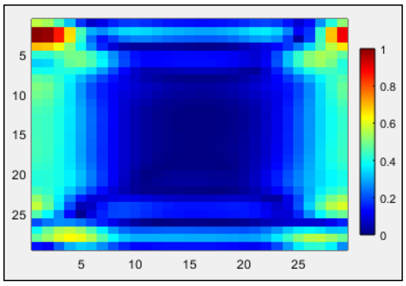
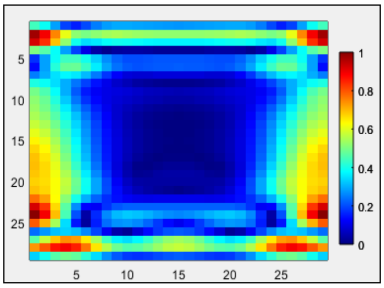
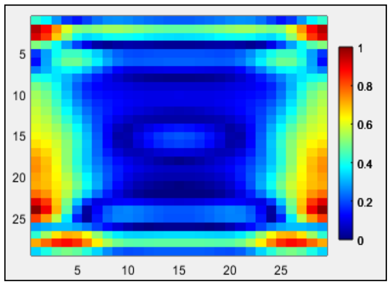


(a) Middle damage (b) Corner damage (c) Side damage

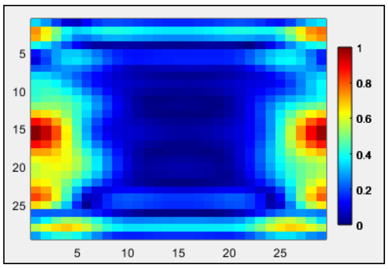


(d) Top damage

Figure 8: Wavelet coefficients of numerical plate model using mode shape difference (two opposite sides fixed)

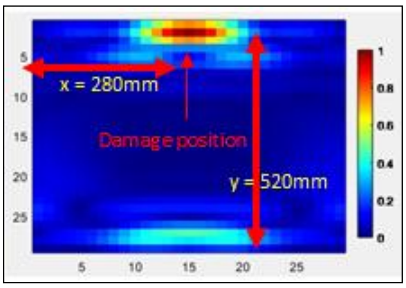




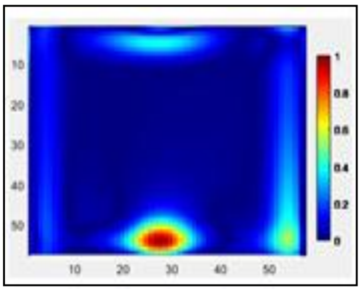
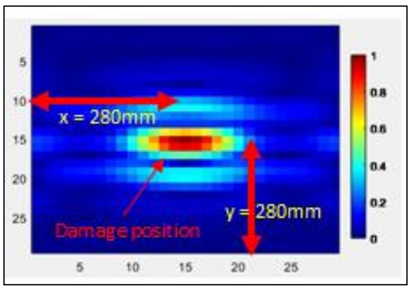
(a) Top damage (b) Mid-support damage (c) Middle damage



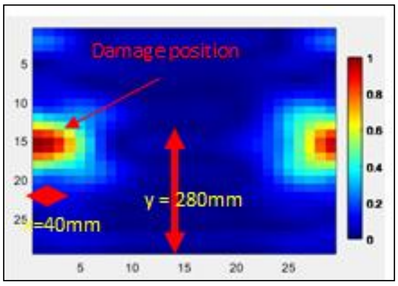
(d) Side damage

Figure 9: Wavelet coefficients of numerical plate model using mode shape (one side fixed)



(a) Top damage (b) Mid-support damage (c) Middle damage



(d) Side damage

Figure 10: Wavelet coefficients of numerical plate model using mode shape difference (one side fixed)

CONCLUSIONS

This study presents a comparison of mode shapes and mode shape differences to detection of damage by using wavelet transform. Numerical models of three square plates with different boundary conditions – four sides fixed, two sides fixed and one side fixed – are applied to make this comparison. The results showed that in detecting damage by using wavelet transform, mode shape differences provided more reliable results than mode shapes. Damages were undetected at some locations in plate models with four sides fixed and two sides fixed when first mode shapes are applied. This study showed that wavelet transform decomposition of cantilever plate first mode shape does not provide any reliable result when damage was imposed at all the different locations. Similarly, the effect of border distortion hinders reliability of results of damage detection when mode shapes are applied. This border distortion problem can be solved by applying the mode shape differences. Lastly, the application of mode shape differences is preferable.

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REFERENCES

[1] Gałka, J., and Ziolko, M., 2009, "Wavelet parametrization for speech recognition," In Proceedings of an ISCA tutorial and research workshop on non-linear speech processing NOLISP 2009, VIC 2009.

[2] Lee, D. T. L., and Yamamoto, A., 1994, "Wavelet Analysis: Theory and Applications," Hewlett-Packard Journal.

[3] Law, S. S., and Li, X. Y., 2007, "Wavelet-based sensitivity analysis of the impulse response function for damage detection," Journal of Applied Mechanics, ASME, 74 pp. 375-377.

[4] Konar, P., and Chattopadhyay. P., 2011, "Bearing fault detection of induction motor using wavelet and Support Vector Machines (SVMs)," Applied Soft Computing pp. 4203-4211.

[5] Pnevmatikos, N. G., and Hatzigeorgiou, G. D., 2016 "Damage detection of framed structures subjected to earthquake excitation using discrete wavelet analysis," Bulletin of Earthquake Engineering.

[6] Hester, D., and González, A., 2012, "A wavelet-based damage detection algorithm based on bridge acceleration response to a vehicle," Mechanical Systems and Signal Processing, 28, pp. 145-166.

[7] Kim, Y. Y., Lee, H. C., and Lee, Y. W., 2000, "Damage detection in a beam via the wavelet transform of mode shapes," The Korean Society of Mechanical Engineers, 24, pp. 916–925.

[8] Hong, J. C., Kim, Y. Y., Lee, H. C., and Lee, Y. W., 2002, "Damage detection using the Lipschitz exponent estimated by the wavelet transform: applications to vibration modes of a beam," International Journal of Solids and Structures, 39, pp. 1803-1816.

[9] Gentile, A., and Messina, A., 2003, "On the continuous wavelet transforms applied to discrete vibrational data for detecting open cracks in damaged beams," International Journal of Solids and Structures, 40, pp. 295-315.

[10] Fan, W., and Qiao. P., 2009, "A 2-D continuous wavelet transform of mode shape data for damage detection of plate structures," International Journal of Solids and Structures, 46 pp. 4379-4395.

[11] Xiang, J. and Liang M., 2012 "Wavelet-Based Detection of Beam Cracks Using Modal Shape and Frequency Measurements," Computer-Aided Civil and Infrastructure Engineering, 27, pp. 439-454.

[12] Bai, R. B., Ostachowicz, W., Cao, M. S., and Su, Z., 2014, "Crack detection in beams in noisy conditions

using scale fractal dimension analysis of mode shapes, Smart materials and structures, 23, 065014.

[13] Amiri, G. G., Jalalinia, M., Hosseinzadeh, Z., and Nasrollahi, A., 2015, “Multiple crack identification in Euler beams by means of B-spline wavelet,” Arch Appl. Mech., 85 pp. 503-515.

[14] Alamdari, M. M., Li, J., and Samali, B., 2015, “Damage identification using 2-D discrete wavelet transform on extended operational mode shapes,” Archives of civil and mechanical engineering, 15, pp. 698-710.

[15] Gholizad, A., and Safari, H. 2016, “Two-Dimensional Continuous Wavelet Transform Method for Multidamage Detection of Space Structure,” Journal of Performance of Constructed Facilities, 30, 04016064.

[16] Abdulkareem, M., Bakhary, N., and Vafaei, M., 2015, “Application of Wavelet Transform to Damage Detection in Plates using Response-only Measurements,” 16th Asia Pacific Vibration Conference 24-26, HUST, Hanoi, Vietnam.

[17] Mallat, S. A., 1998, Wavelet Tour of Signal Processing. Academic Press, New York.

[18] Rucka, M., and Wilde, K., 2006, “Application of continuous wavelet transform in vibration based damage detection method for beams and plates,” Journal of Sound and Vibration, 297, pp. 536-550.

[19] Computers and structures, i., SAP2000. 2014. Version 17.1.1.

[20] Rucka, M., 2011, “Damage detection in beams using wavelet transform on higher vibration modes,” Journal of theoretical and applied mechanics, 49, pp. 399-417.

[21] Ovanesova, A. V., and Suárez, L. E., 2004, “Applications of wavelet transforms to damage detection in frame structures,” Engineering Structures, 26, pp. 39-49.

[22] Reda Taha, M. M., Noureldin, A., Lucero, J. L., and Baca, T. J., 2006, “Wavelet Transform for Structural Health Monitoring: A Compendium of Uses and Features,” Structural Health Monitoring, 5, pp. 267–295.