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Application of DIC method to modal vibration study for structure health monitoring of WT tower

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ABSTRACT

In recent years, wind power generation has been widely promoting by government policy. If the structural health of wind turbines can be screened effectively and quickly, the cost for operation and maintenance will be reduced. Such techniques are desirable since a vast number of wind turbines are scheduled to be operational in the next decade in Taiwan. This certainly sets the stage for research on developing the vibration analysis and monitoring techniques for the supporting structure of wind turbine (WT) systems. The authors demonstrated in a previous study that the defect location can be discovered using the frequency displacement mode output of the numerical model. In the current study, a PVC pipe with a mass attached at the top has been applied to validate the results of the numerical simulation. The displacement in three axes of each target of equal spacing on the PVC pipe is determined by using a technique based on digital image correlation. The resulted first modal vibration pattern in the frequency domain can be linked to the dynamic behaviour of this sized-reduced model of the wind turbine tower. The experimental data show that the proposed method has a good potential for damage assessment.

Keywords: DIC, Vibration, Wind turbine tower, Structure health monitoring.

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1. INTRODUCTION

Developing structural health monitoring techniques for wind turbine (WT) systems is critical for the operation and maintenance of large-scale wind farms. The authors demonstrated in a previous study (Lin et al., 2019) that the defect location can be discovered using modal responses obtained from displacement outputs simulated by numerical models. A fast detection scheme was developed using the modal curvature index. It was calculated by the scale of the amplitude value of displacement in the frequency domain. In a related study, the natural frequency of the 25-kW wind turbine was 0.44 Hz measured by IBIS (Image by Interferometric Survey), a long-range microwave radar system (Chiang et al., 2018). However, the reflected points on the tower may vary in the follow-up inspection. The ability to assess the variation of modal shapes of the wind turbine tower is thus limited. Also, when dealing with a small scaled model, the blind range of the radar facility limits its applicability. Digital image correlation (DIC) techniques have been extensively explored for strain measurements of WT blades (Wu et al., 2019), and vibration analysis and displacement measurements of bridges and towers (Ngeljaratan and Moustafa, 2019). The focus of the current study is the effectiveness of using an equivalent vibration shape of the first mode of a small-scale wind turbine model (WT model) to carry out a scheme of detecting the defective region of the WT tower.

2. THEORETICAL BACKGROUND AND METHODOLOGY

2.1 Modal Curvature Index

The ensemble of the amplitude of the fist mode of multiple points along the cantilever structure in the frequency domain can be used to approximate the first mode shape (Lin et al., 2019; Lin et al., 2020). There exists a lot of research on wind turbine health monitoring that focused on the change of mode shape due to defects (Nguyen et al., 2017; Wout et al., 2017; Oliveira et al., 2018). Nonetheless, the development of effective techniques in performing quantitative evaluation is still in demand. The curvature index method is a relatively simple approach, which can be easily interpreted with two modal curvatures measured at different times, and the modal curvature (D'') can be calculated by Equation (1).

$$D''_{i,avg} = \frac{D_{i-1} - 2D_i + D_{i+1}}{(\Delta l)^2} \quad (1)$$

D_i: the displacement of ith point.

Δl : the interval of measured points.

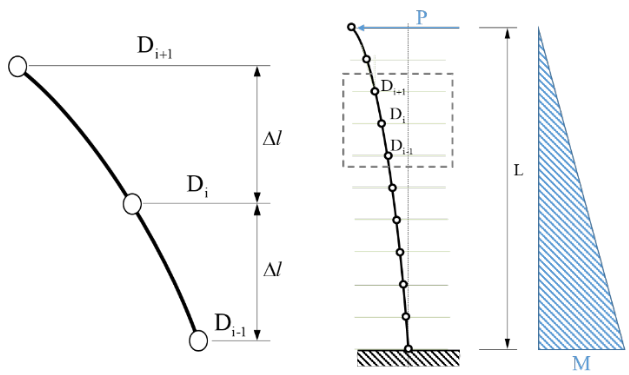


Fig. 1. Schematic of modal curvature measurement (Lin et al., 2019)

Unlike methods using changes in multi-mode shapes, this method only requires an approximate mode shape. Because the first mode contains more energy, the amplitude profiles obtained with the frequency responses at the first vibration frequency can be considered as an equivalent shape of the first mode. For an intact member with uniform cross sectional properties, the first mode shape is continuous. As certain defects exist, the variation of the curvature shows non-smooth jumping when the measurements at two different times are compared. Accord to this idea, the curvature index $\Delta\Phi_i$ is proposed to observe the health condition of the WT tower in this research. As defined in Equation (2), the modal curvature of each defect-free node κ_n^i is used as the benchmark and the corresponding modal curvature after the structure is damaged is termed as κ_d^i. By subtracting the two quantities, the change in the modal curvature is defined as curvature index as:

$$\Delta\Phi_i = \kappa_d^i - \kappa_n^i \quad (2)$$

2.2 Digital Image Correlation (DIC) Method

DIC is an image processing technique that includes registration and tracking for accurate 2D and 3D measurements. This technique is often used to measure full-field deformation or tracing the moving path of objects. Researchers have applied DIC in many areas of science and engineering since 1980s (Anuta, 1970; Keating et al., 1975). In this paper, the open software DICe (Digital Image Correlation Enging) developed by Turner (2017) is used to capture the deformation of the scaled WT model. The DIC method relies on finding the maximum of the correlation array between the subsets of the pixel intensity array in two corresponding images, which gives the translational shift of the point of interest.

3. EXPERIMENT

3.1 Experimental Design and Setup

This paper consists of two parts of studies: one is the investigation of the effect of different external loadings on the dynamic responses of the WT model, and the other is the exploration on the difference of the dynamic responses for defective WT towers. First of all, the displacement responses of the WT model without artificial defects are measured by the DIC method and the accelerometer simultaneously. The artificial defect is next added to the WT model prior to the second measurement of the dynamic response. Fig. 2 shows the research flowchart, in which the modal shape due to different excitations and due to different degree of defects are compared. In addition, the modal curvature and curvature index are also calculated to quantify the effect due to the defect.

A PVC tube of 1020 mm in length is used to model a wind turbine tower. The tube has an outer diameter of 3.4 cm and a wall thickness of 3 mm. A 0.38-kg mass block consisting of four bolts and a 400*400 mm steel plate is attached to the top of the tube. The excitation forces are generated by a 0.615-kg weight or a 0.411-kg weight through a pulley system. The weight is connected to the top of the pipe with a cotton thread. The installation is shown as Fig. 3(a), when the cotton thread is cut, the weight will be released. The artificial defect is made by cutting the pipe with 1- cm width and the thicknesses of the cutting area are 1 mm, 2 mm, and 2.5 mm, respectively. An accelerometer is deployed near the top of the scaled WT model. The scaled WT model is shown in Fig. 4, in which each target on the WT model is spacing with a 50 mm interval. There are 9 targets from the bottom to the top. The position of the artificial defect is near the center between target 4 to target 5.

3.2 DIC Settings

In this study, the 3D-DIC method is used to measure the displacements in three directions of the tower. Nine feature targets with a uniform spacing are used, each consists of a 20*20 mm beacon with irregularly distributed noise points on the surface. The two cameras are set 480 mm apart. The distance from the camera to the target is 1200 mm, as shown in Fig. 5. The height from the center of the camera lens to the floor surface is about 1450 mm. Since the instruments are re-positioned during different measures, there exists a 3~5 mm difference among different measurements.

Two Sony alpha-9 digital cameras are set to the video mode with a shutter speed of 60-frame per second. The images captured from the video have a resolution of 1920*1080 pixels. The parameters of the subset are 27~31 pixels and the step are 11~15 pixels. While this method is considered as a least-squared fit of the triangulated space system in which a best-fit plane is selected, the resultant coordinate systems are a bit different in two operations (Turner, 2017).

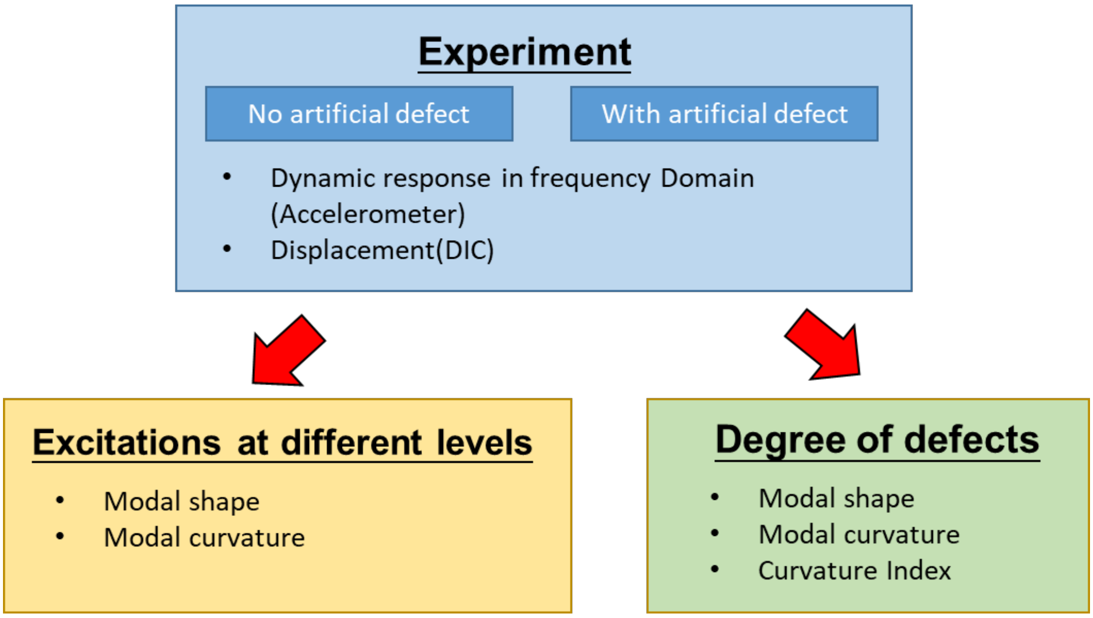


Fig. 2. Illustrations of research themes

(a) (b)

Fig. 3. Small scaled WT model: (a) Installation of excitation force system (b) Artificial defect

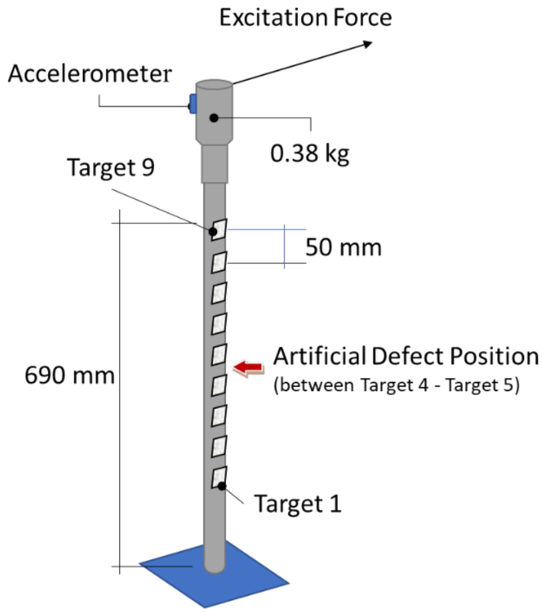


Fig. 4. Set up of the scaled WT model

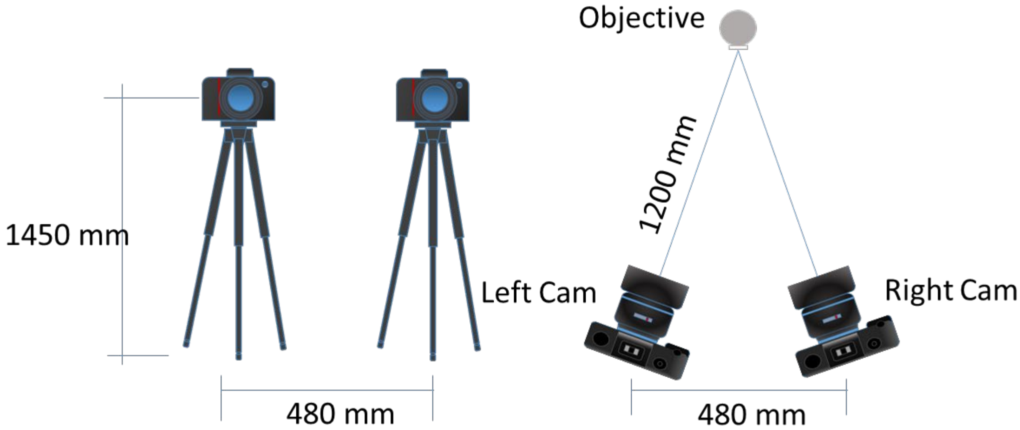


Fig. 5. Layout of the cameras and target

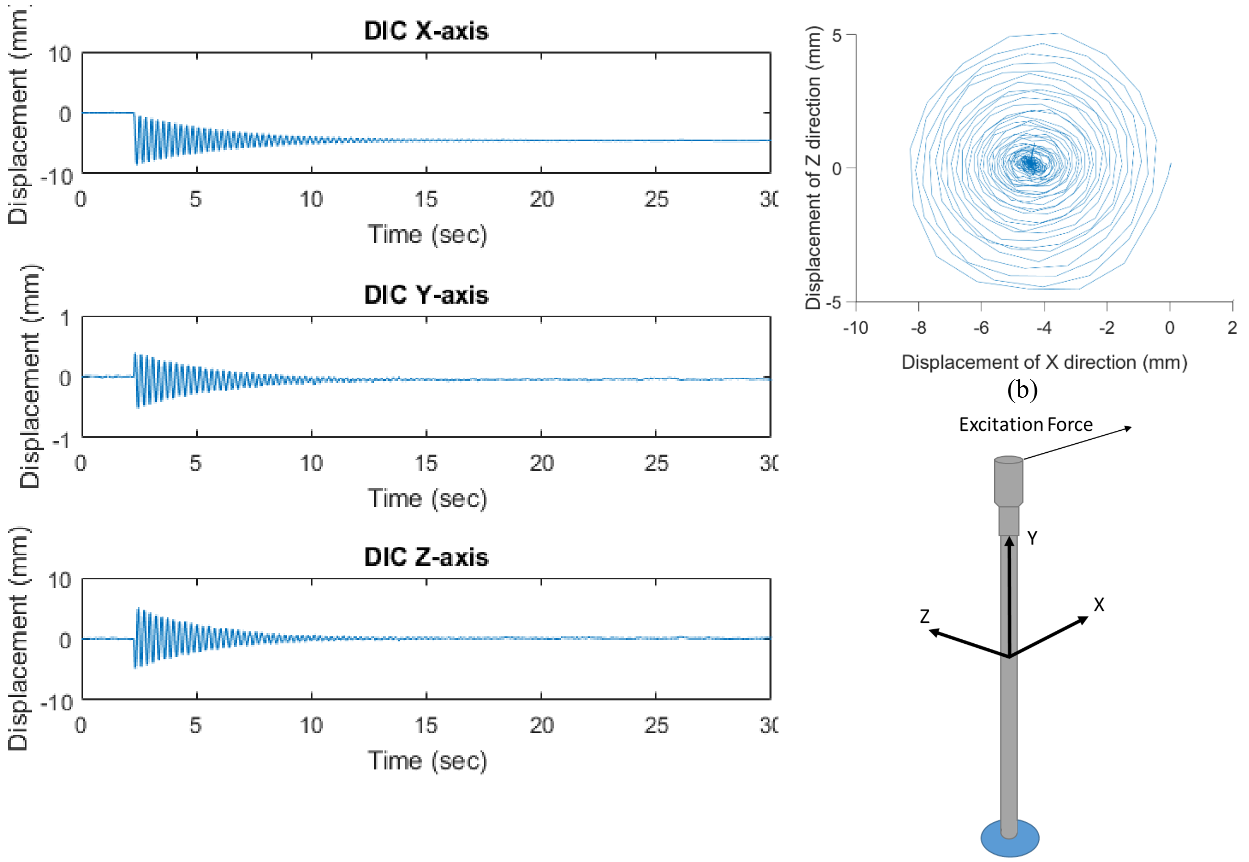
4. EXPERIMENTAL RESULTS

4.1 Dynamic Response of Scaled WT Model

The dynamic responses shown in Fig. 6 is the movement recorded by the DIC method of the top target. A circular or elliptical motion of the tube can be observed. Because the excitation forces are added after the start of recording then release, the displacement response does not go back to zero at the end of the recording, especially for the response in the X direction.

The first mode frequency of the scaled WT model without the artificial defect is about 3.9 Hz, as measured by the accelerometer and shown in Fig. 7. When the damaged scaled WT is tested, the first mode frequency decreases with increasing thickness of the artificial defect, but not sensitive. It is difficult to tell the difference in defect effect. The DIC method obtains results similar to the accelerometer measured responses, as shown in Fig. 8.

The typical amplitude variations of the first mode, which are obtained from the amplitudes of the frequency response of nine targets, are shown in Fig. 9(a) and (b). The amplitude variations of the two coordinate directions on the horizontal plane are similar to the mode shape of a cantilever beam. The amplitude variation in the vertical direction, however, is different from the horizontal ones, as in Fig.9(c). Fig. 10(a) shows the effect due to different excitation forces. The amplitude variations of three measurements are similar in shape with different scales even exited by the same force. To facilitate the comparison of different measurements, normalization is obtained from the amplitude of each target divided by the lowest one. Shifting the lowest one to the zero, the results are shown as Fig. 10(b). It is obvious that the various normalized curves are very consistent with each other in both shape and scales. The normalized curve is similar to the mode shape of the first mode, thus it is taken as an equivalent mode shape throughout the paper.



(a) (b) (c)

Fig. 6. Dynamic responses of the top target (a) displacement responses in 3 directions (b) plane movement of the target on x-z plane (c) coordinate system

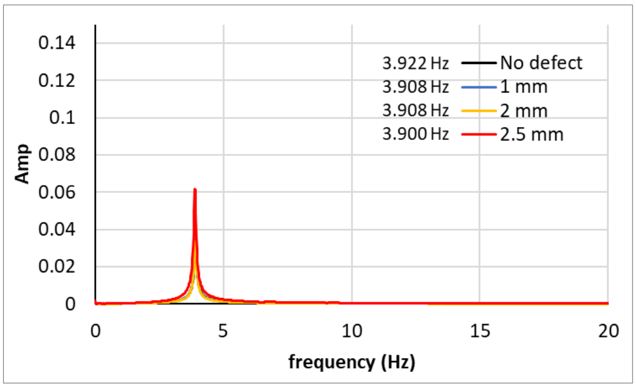


Fig. 7. The frequency spectra of the accelerometer on top

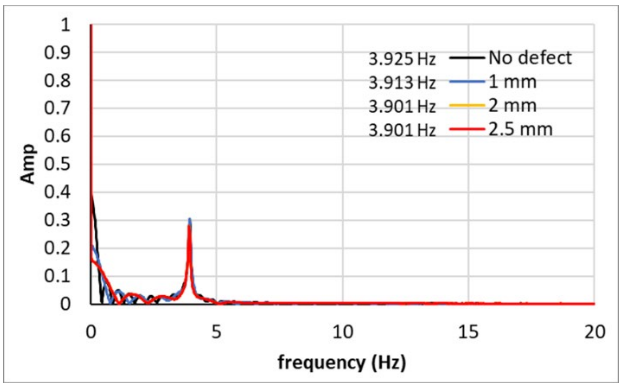


Fig. 8. The frequency spectra of the displacement by DIC

By averaging all measured results of the same defect condition, the representative mode shape can be obtained. In general, the equivalent mode shapes in the X and Z directions are identical to the results without defect. On the other hand, significant changes can be obtained from the results in the Y direction. Significant changes are observed from target 4 through target 6, as shown in Fig. 11.

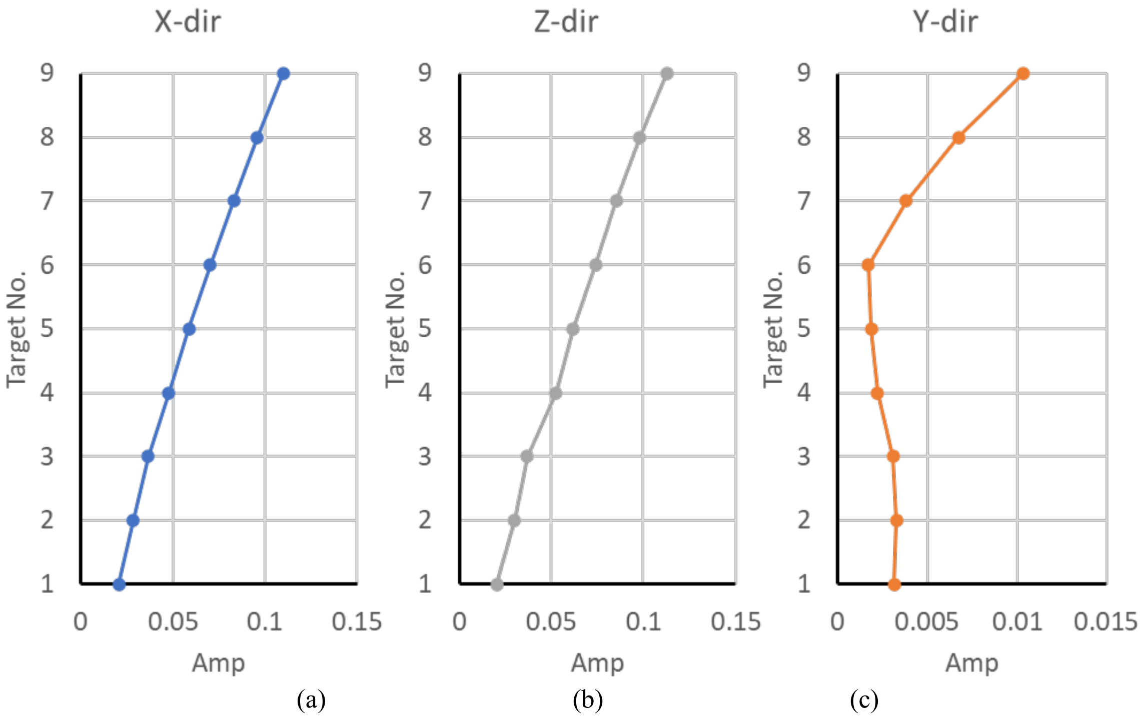


Fig. 9. The typical amplitude curves of the scaled TW model due to an excitation at the top (a) X-direction (b) Z-direction (c) Y-direction

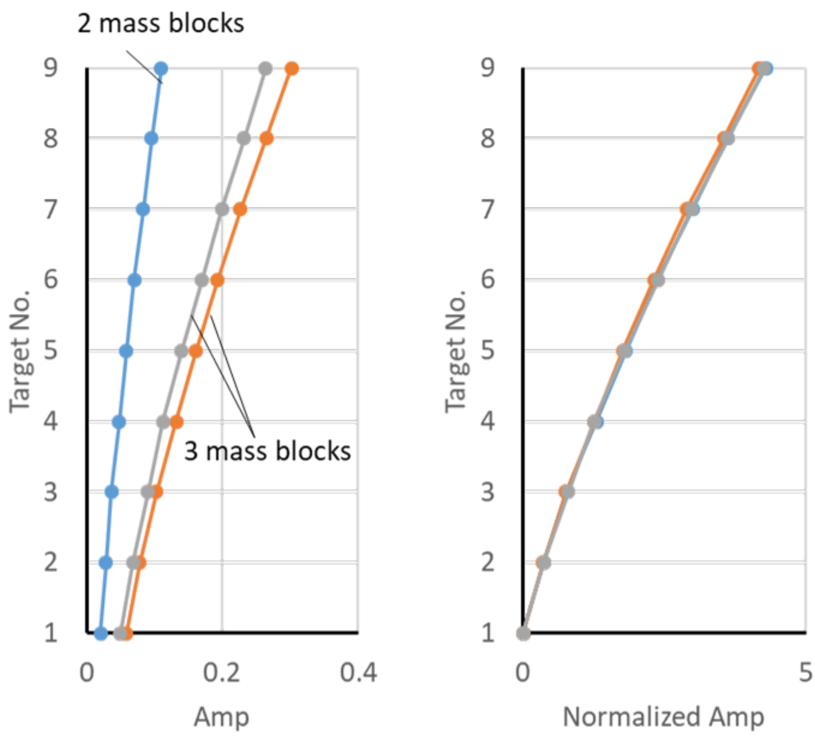


Fig. 10. The amplitude curves due to different excitations (a) normalized amplitudes of the scaled TW model (X-direction) (b) defined equivalent mode shape

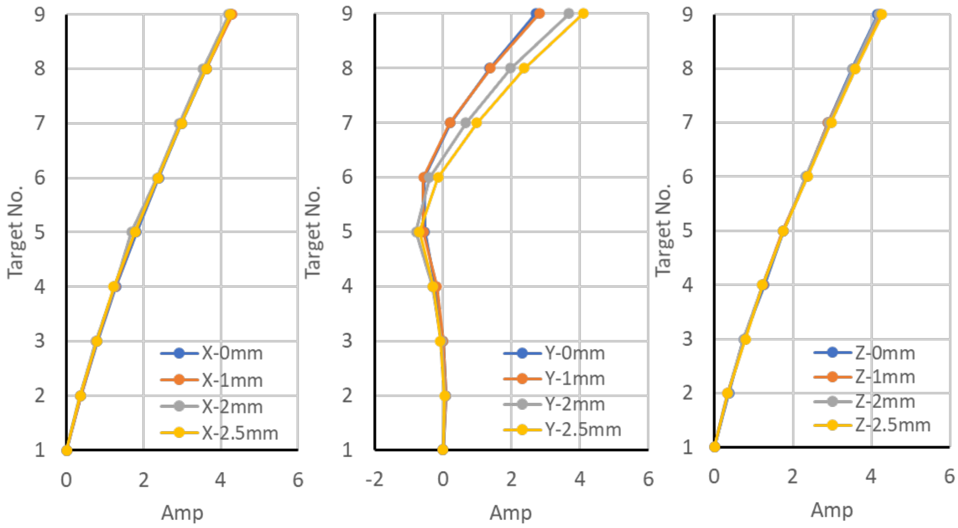


Fig. 11. Equivalent mode shapes for different sets of defects

4.2 The Modal Curvature and Curvature Index

Based on the above-mentioned equivalent mode shape, the modal curvature can be calculated by Equation (1). Fig. 12 shows the modal curvature corresponding to the first vibration mode for the three directions, namely X, Y, and Z. The modal curvatures in the X and Z directions are similar before and after being damaged, thus no obvious defect can be identified. For larger defects such as the 2 mm and 2.5 mm samples, higher values of modal curvature near the target 5 position can be seen. Moreover, the modal curvature curves show relatively significant jumps for the 2-mm and 2.5-mm defects in the Y direction. The values of curvature index clearly indicate significant changes due to the defects larger than 2 mm. The curvature index at target 5 appears to decrease with increasing depth of the defect, as shown in Fig. 13. As a result, the modal curvature and curvature index computed by Equation (1) and (2) can be used to highlight the abnormal responses induced by the artificial defect. By cross examining the curvature indices obtained in the three directions, the possible location of the most damaged portion can generally be determined.

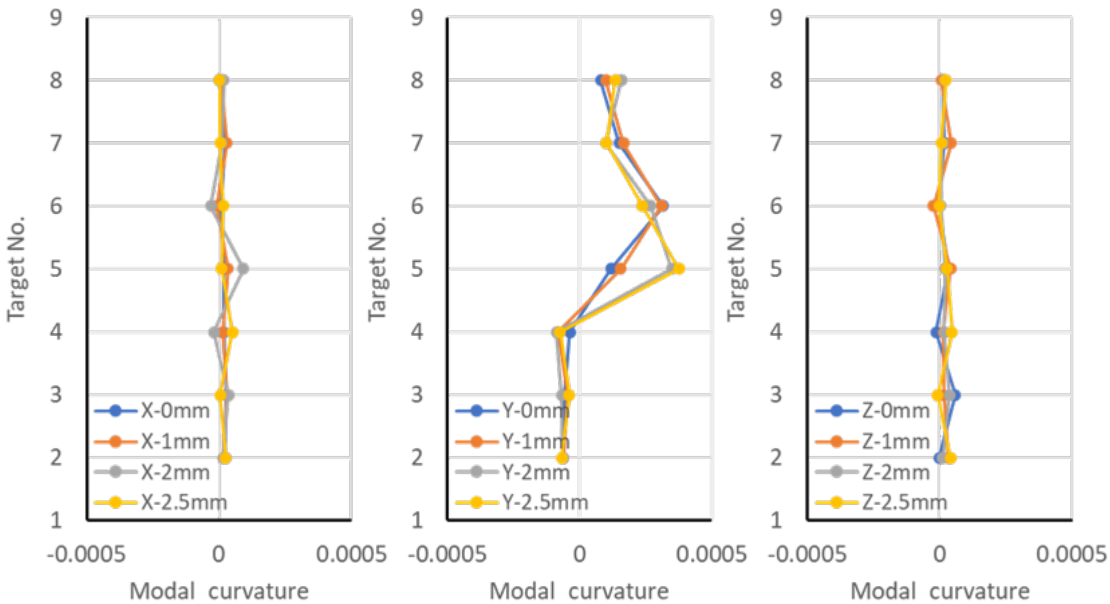


Fig. 12. The computed modal curvatures due to different defects

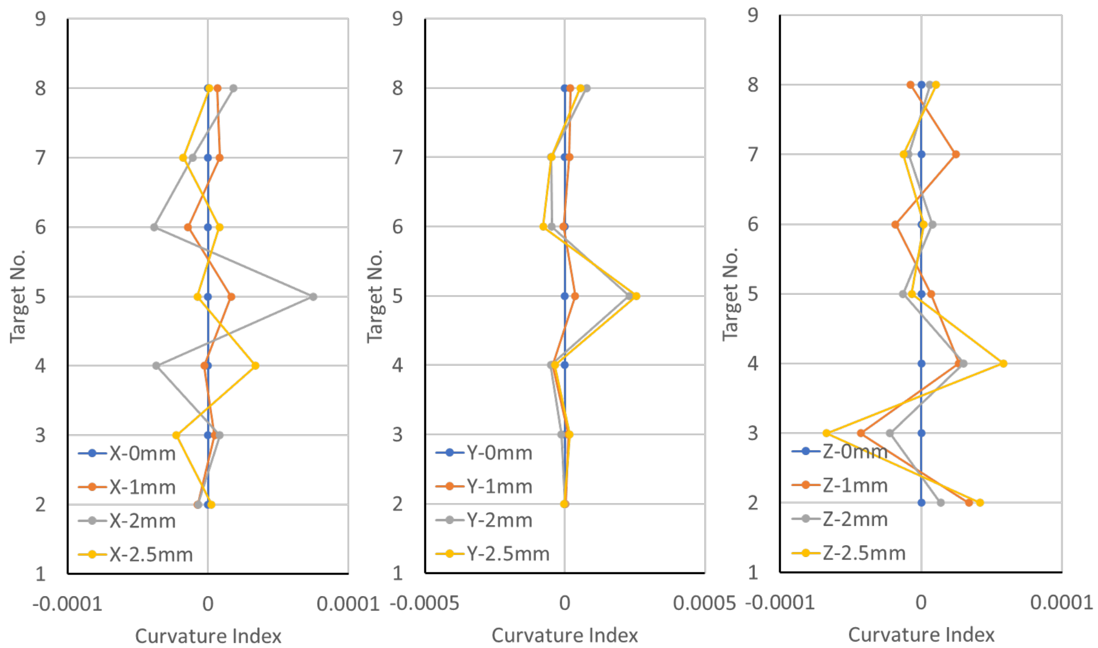


Fig. 13. The corresponding curvature index for different defects

5. CONCLUSIONS

5.1 Modal Curvature Index

- In this study, the area of the artificial defect is about 1/20 of the full section, which is difficult to be detected by observing the changes in the modal curvature data. However, by calculating the variation of the defined curvature index, the indication of possible regions of the defect can be enhanced. In addition, the curvature index in Y-direction seems to provide clear indication when the defect depth is large than 2 mm. Further investigation is necessary for analyzing the curve inflection in all measurements at targets from no. 6 to no. 7.
- The curvature index seems to be a promising technique for health monitoring of the support structure of wind turbines. Further research will focus on the detection of the damages at multiple positions in the WT model.

5.2 DIC Measurement in the Larger Structures

- DIC technique proves to be effective for indoor experiments. The main advantage is that the more measured points are used, the denser mode shape would be obtained. It is helpful to the analysts when observing the changes of mode shapes and modal curvature curves. However, DIC method requires a full-scale calibration board in the focal plane, which limits its efficiency to the field application to WT towers. More research work is underway on alternative calibration methods using the virtual image system and AI.

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