A Simplified Wind Turbine Blade Crack Identification Using Experimental Modal Analysis (EMA)

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Received: 19.11.2016 Accepted:02.01.2017

Abstract- Wind turbines blades rotate and flutter in extreme weather and fatigue loading conditions while subjected to random wind speeds. Furthermore, the wind turbines are usually located in remote areas with elevated heights thus difficult to be reached, examined, and assessed. Therefore, performing maintenance and repair is very challenging process due to the difficult and limited machine accessibility. The wind turbine blades conditions have significant contribution to turbine durability, reliability and performance issues, practically for offshore and megawatt-class wind turbines. Hence, to ensure their proper functioning, a robust condition monitoring system (CMS) for early detection of blade deterioration to be developed and implemented. Experimental modal analysis investigates the effect of structure dynamics variations, which may result from the presence and propagation of cracks, on the behaviour of the vibrational modal parameters including modal frequencies, modal shapes and damping. To enable the emulation of wind turbine blades, a stepped beam is used in this paper to examine the application of experimental Modal Analysis technique in identification of blade fault. The aim is to assess the applicability of using the experimental modal analysis as a structural health monitoring (SHM) approach for wind turbine blades. An impact hammer test has been performed for the stepped beam with different crack sizes located at predetermined places. The Frequency Response Function (FRF) has been obtained experimentally as the frequency response ratio of the structure output to the input excitation force, $H(\omega) = X(\omega)/F(\omega)$. The stepped beam FRF has been calculated at different impact location and 3D plots are generated to define the structure modal shape. The results proved that the use of modal parameters allow for the detection and estimation of crack size in the stepped beam, hence motivate and provide a reference to investigate its implementation to wind turbine blades.

Keywords Experimental Modal Analysis, Impact hammer test, Wind turbine blade fault identification, Vibration based modal Analysis, Frequency Response Function (FRF).

1. Introduction

Power generation systems based on wind turbines are currently considered one of the main alternatives to the fossil power generation systems and has shown to be the leader of all technologies in new power production in 2015 [1]. Therefore, maintenance processes of wind turbine systems have become a significant factor to enhance the system efficiency and reliability. This has essentially dictates the need to develop a robust and effective maintenance approach considering the large size, complexity and severe working environments of wind turbine systems. Condition Based Maintenance system has the ability to continuously monitor the health of the running machines and reduce the repair and replacing costs especially when the wind turbine located in remote places under severe working conditions [2].

Wind turbine blades are in direct contact with wind and subjected to other environmental factors, such as variable aerodynamic loading (wind speed), heavily rainfall, temperature variation, humidity, erosion etc. As a result, the rotating blades will experience delamination, imbalance and cracking which are the major causes of blade damage. A damaged blade in operation influence not only the efficiency of power production, which reduces because of losses on the aerodynamic profile of the blade, but also on the risk mitigation measures of the surrounding areas, in case of fragments are split out from the rotating blade or turbine fire risk as a result of overheat because of rotating unbalance. Moreover, the wind turbine blades are the most expensive components in the modern wind turbine machine with a complex aerodynamics design profile. Furthermore, the wind turbine blades are fabricated with high and special production technology and materials configuration and form a significant part of the initial capital of wind turbine investment. The vibration based- modal analysis parameters (i.e. resonant frequency, mode shape and modal damping) of a mechanical structure are directly correlated with the structure integrity and can be implemented as potential measures of online wind turbine blade conditions monitoring.

The Finite element based vibrational modal analysis has been applied to wind turbine blade to explore the variation of the modal parameters as a result of presence of blade crack [3]. Agarwalla and Parhib [4] investigated the effect of an open crack condition on the modal parameters of the cantilever beam subjected to free vibration using finite element method (FEM) and experimental method up to 3rd vibration mode. First two modal frequencies of the cracked beam have been obtained experimentally and used by Kaushar et al [5] for the identification of crack position and size. Mathematical model based on the experimental modal frequencies of a cantilever beam has been formulated to identify the beam crack condition. A finite element model as well as experimental modal analysis of a cantilever beam with an inclined open edge crack has been implemented by Ranjan et. al. [6] to predict the crack condition. The fault prediction approaches of both numerical and experimental modal analysis (i.e. modal shapes and frequencies) show that, the vibration magnitude of the first vibrational mode has decreased when the crack is located with more distance from fixed end, however the magnitude of the second and third modes are larger when the crack is far from the beam fixed end under condition of constant crack size and crack inclination angle.

Nandwana and Maitithe [7] simulate the beam crack as a rotational spring and proposed a method involve plot the variation of the beam stiffness versus crack location for three natural vibrational modes. The point of intersection of the three curves estimates the crack location and the corresponding stiffness value. The crack size is then computed using the standard relation between stiffness and crack size. In Khiem and Lien [8], the multiple cracked beam identification process has been formulated as a non-linear optimization problem based on its natural frequencies. Bing et al [9] investigate the application of wavelet analysis and fractal dimension (FD) as a hybrid approach to estimate the crack location in beam structures. Wavelet analysis with B-spline wavelet mother function has been implemented as a composition method for the cracked beam mode shape. The proposed hybrid method shows a high success rate of crack recognition even for complex structures. Amit et al [10] formulate a fuzzy controller to predict the crack size and location in beam based on the vibrational modal frequencies which are obtained numerically through ANSIS finite element model. Zang et al [11] illustrated the crack identification method combining wavelet analysis with transform matrix. The crack location was determined through the peaks of the wavelet coefficients and the crack location has been defined based on a simple transform matrix method. A simplified model of the turbine blade as a cantilever beam has been applied by Prakash [12]. An online crack diagnostics method in turbine blades has been developed for open U-notches cantilever beams based on finite element modal analysis using ANSIS software.

Behera and Parhi [13] investigate the application of different fuzzy controllers based finite element analysis as intelligent inverse analysis approach to study the correlation between the modal parameters (i.e. modal frequencies and mode shapes) and crack condition (i.e. crack size, crack location and crack inclination angle) of an inclined edge crack in a cantilever beam. Khiem and Lien [14] investigate the application of transfer matrix method to evaluate the natural frequency formula of a beam with an arbitrary number of transverse cracks, the crack has been simulated as a rotational spring model. The frequency formula has been used to predict the number of cracks its size and location. Shinde and Katekar [15] represent a crack diagnostics method based on the of vibration response of a cantilever beam with single open transverse crack at different loading conditions. In transverse load condition a spherical defined mass is dropped from a certain elevation on free end of cantilever beam. The results show that, the beam natural frequency drops as crack depth is developed and natural frequency is higher when the crack location moved towards the fixed end of the beam. Tartibu et al [16] examined the correlation between the experimental modal parameters and fault conditions in a wind turbine blade (approximated by a cantilever stepped beam). The experimental results have been validated by the exact solution of an Euler-Bernoulli beam. Tartibuet et al [17] approximate the blade structure by a two stepped beam with solid and hollow sections using a MATLAB-finite element model for a one dimensional beam. Furthermore, a three dimensional finite element stepped beam model has been developed with Unigraphics NX4 software. The effects of varying the blade length on the natural frequencies have been presented. Zhao [18] used strain sensor instrumentation system for wind turbine blade condition identification. The strain sensor system can function in an environment with high moisture absorption, fatigue loading, strong blast of wind and lightning strikes. Kim et al [19] presented a structural health monitoring (SHM) method to detect wind turbine blade cracks using the Vibo-Acoustic Modulation technique. Anne [20] investigates the application of the acoustic resonance spectroscopy as a wind turbine blade inspection and fault detection method.

In this paper the wind turbine blade Figure 1-a has been approximated by a variable width beam (stepped beam) Fig. 1-b, for the purpose of investigating the potential correlation between the modal parameters and the crack condition which is essential of applying the experimental modal analysis as wind turbine blade fault detection approach.

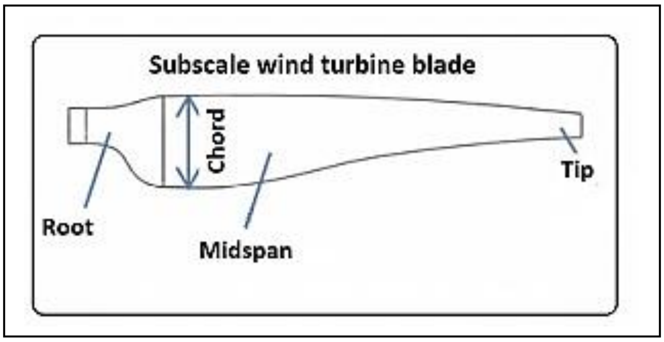

Fig. 1-a. The actual blade profile

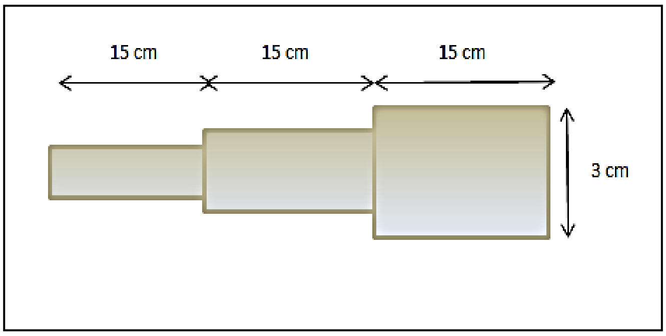

Fig. 1-b. The simplified profile (stepped beam).

2. Vibration Based Modal Analysis

The structural and mechanical systems appear to be in stationary condition but actually it have oscillatory motion (vibration) as a function of time. The oscillatory motion takes different patterns (mode shape) and vibrate at specified frequency (modal or resonant frequency) and damping (modal damping) the so called "modal parameters". Theses parameters depend on the mechanical/material properties of the structure (i.e. mass, damping and stiffness) and boundary conditions. If either the mechanical properties or the boundary conditions of a structure change, its modal parameters will change.

To understand the basic principles of modal analysis, assume the linear motion (x) of Mass (M) - Spring (K) – Damper (C) as a single degree of freedom system under an excitation force F (t), the equation of motion is given by:

$$M\,\ddot{x} + C\,\dot{x} + K\,x = F(t) \tag{1}$$

With a transfer function of:

$$H(s) = \frac{X(s)}{F(s)} = \frac{1}{Ms^2 + Cs + K} \tag{2}$$

In frequency domain, the frequency response function (FRF) is defined as:

$$H(\omega) = \frac{X(\omega)}{F(\omega)} = \frac{1}{(K - M\omega^2) - i\,C\omega} \tag{3}$$

Realistically, the wind turbine blade is modelled as a continuous structure with an infinite degree of freedom and modes. For N modes, M, C and K are (N by N) vectors and F is (N by 1) vector.

In experimental modal analysis, each FRF measurement can be arranged as an element of the matrix, $H_{i,j}(\omega)$, so called mobility matrix, *H(ω)* with (N x N) input/output combination. The overall structural frequency response can be approximated as the summation of FRF curves due to each mode (k):

$$FRF(\omega) = \frac{Response(\omega)}{Excitation(\omega)} = H_{i,j}(\omega) \cong \sum_{k=1}^{N} H_{K,ij}(\omega) \tag{4}$$

where, *H_(i,j) (ω)* is the frequency response of the ith degrees freedom due to the applied at the mass point j. For example, H_{12} is the frequency response function of the point mass 1 where the unit impulse is applied at point 2.

3. Experimental Setup

The experimental modal impulse frequency response functions (FRFs) are calculated using the experimental setup shown in Figure 2. Cantilever stepped beams with known dimensions have been fabricated. Different crack depths of 1 mm, 2 mm, 3 mm and 4 mm were deliberately introduced on these beams at a predefined locations, Figure 3. A B&K Piezoelectric IEPE Accelerometer type 4507B has been mounted near the free end of the stepped beam to record the system response x(t), B&K impact hammer Type 8206 with IEPE Force Transducer type 8230 is used to apply and measure the impact excitation force F(t). Both sensors are connected to PULSE LAN-XI Hardware type 3160-A-042 with 4 inputs and 2 output channels, the collected data transfer through LAN cable to PC with B&K PULSE software for data analysis, Figure 4. A modal analysis project has been developed to calculate the FRF of the collected system data, Figure 5.

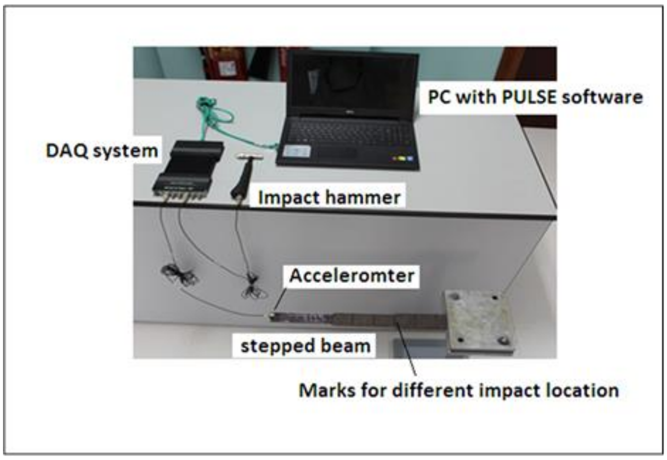

Fig. 2. The Impact Hammer Test Experimental Setup.

4. Vibration Based-Modal Analysis

4.1. Modal Frequency

The total acceleration frequency response function *H_(i,j) (ω)*, to impact excitation is sampled up to 5th modal frequency with averaging of 10, for stepped beam with different crack size at 8 predetermined impact locations is shown in Figure 6.

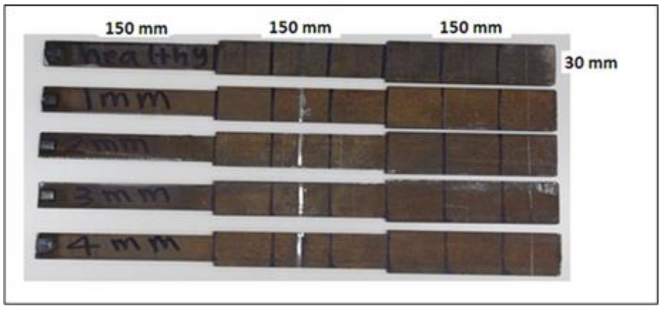

Fig. 3. The Fabricated Stepped Beams with Different Fault Size.

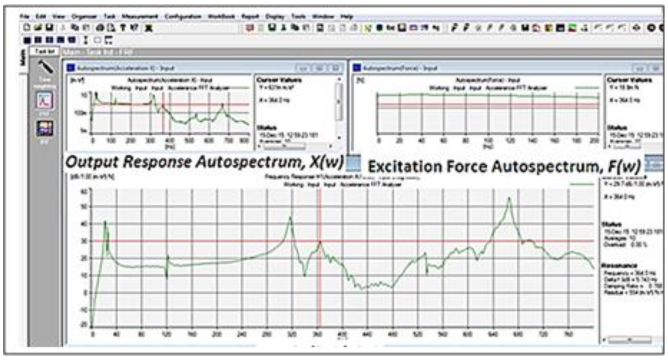

Fig. 4. The calculation of FRF of the beam with PULSE software.

A drop in FRF spectrum peaks frequency (i.e. modal natural frequencies) is clearly observed as a result of increasing of the fault size. For instance, the 5th modal frequency considerably decrease in comparison between healthy and cracked beam with different crack size, Table (1). Figure 7 shows how the FRF 5th modal frequency behaves with different crack size, where it can be clearly seen that it tends to reduce with larger fault sizes, therefore this can provide a valid monitoring parameter to assess the condition of the blade.

4.2. Modal Shape

The FRF of the beam with different impact location of healthy, 1 mm, 2 mm, 3mm and 4 mm crack depth beam are shown in Figure 8. The modal shape is developed by connecting of the corresponding *FRF (jω)* frequency peaks at different impact locations. The modal shape response from the faulty part provides a considerably different pattern in comparison to the healthy part, therefore, the use of modal shape analysis may provide a valid conditioning monitoring parameter to blade crack identification.

4.3. Modal Damping Ratio

The beam damping ratio at different crack size and different impact locations are shown in Figure 9. It can be seen that the damping is increased when the crack in first introduced and then the damping tends to decrease while the crack size is developed. However, the damping ratio parameter requires further investigation to properly set monitoring criteria for the condition monitoring of the part.

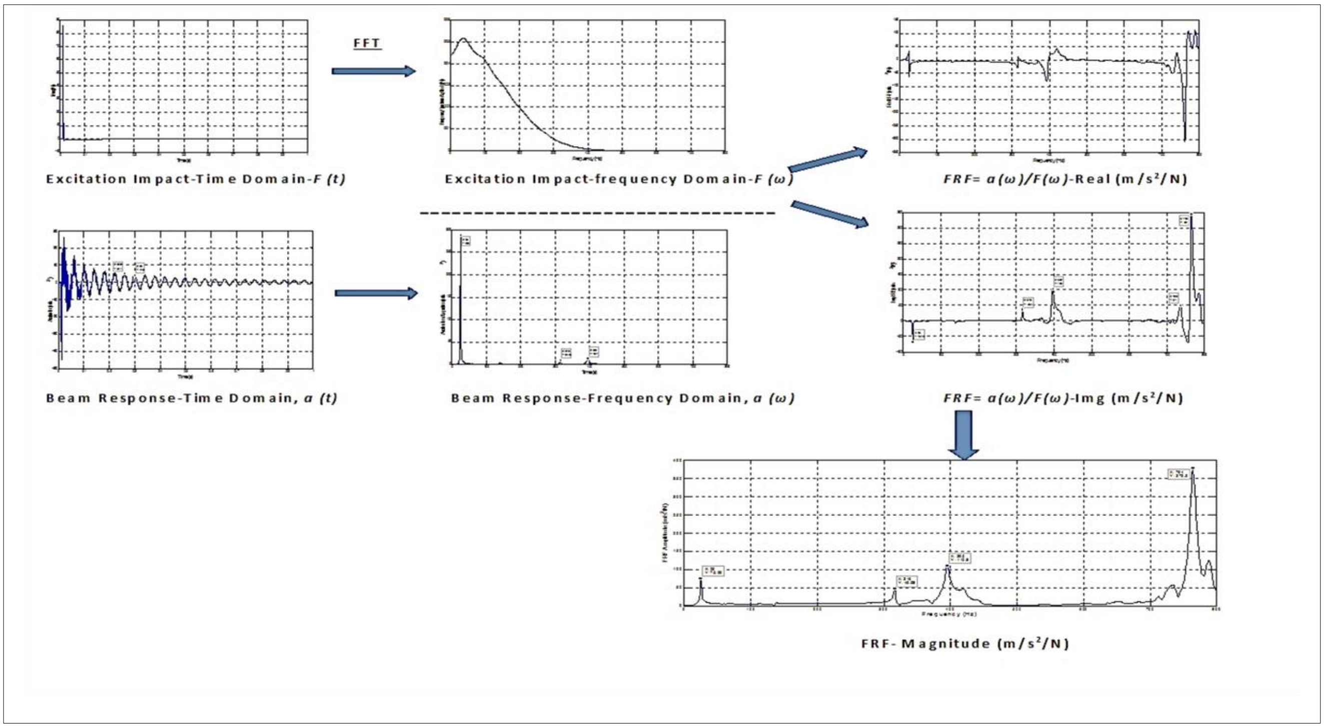

Fig. 5. The FRF computational procedure

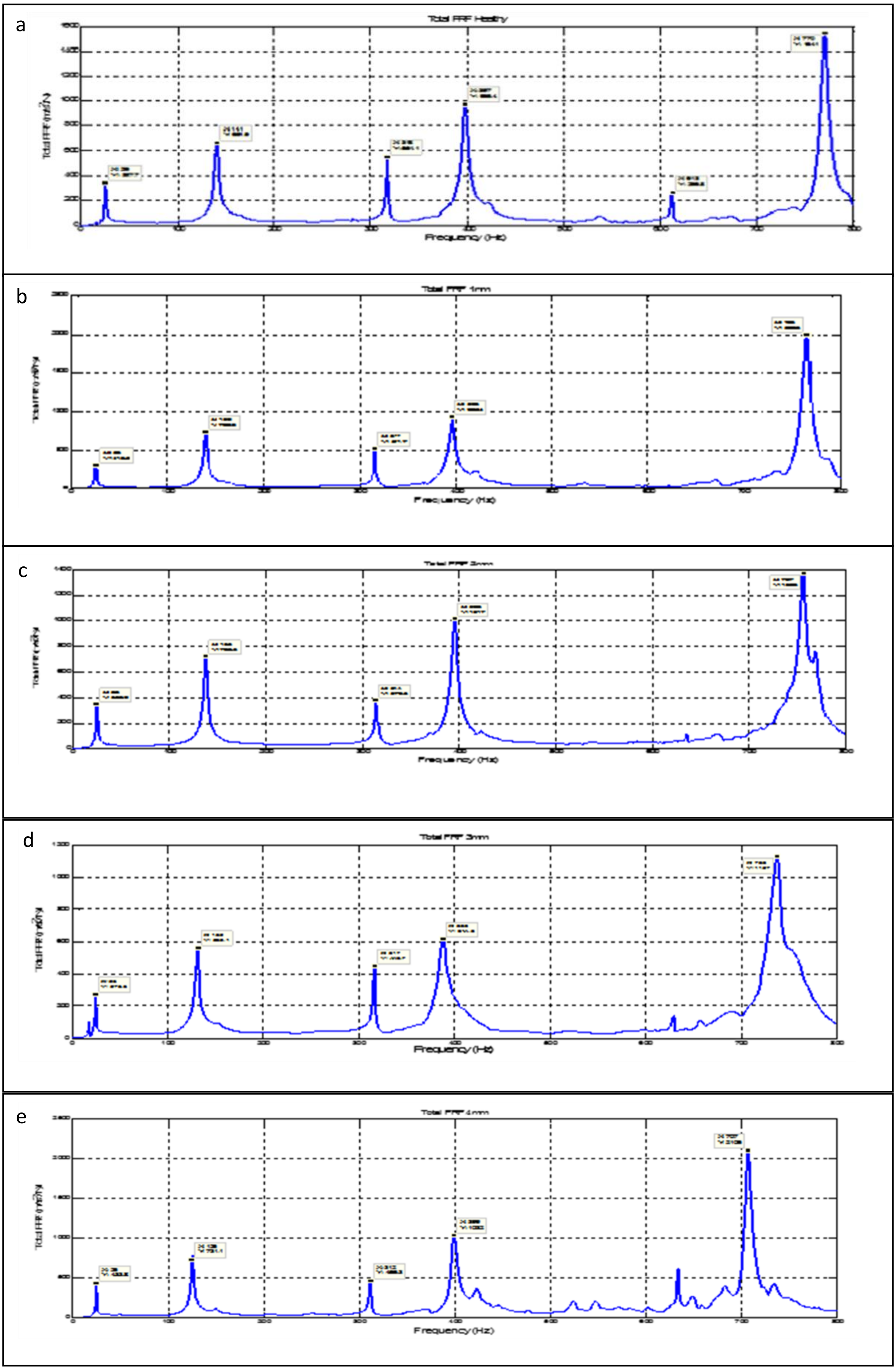

Fig. 6. The total averaged FRF for stepped beam with different fault size: (a) Healthy, (b) 1mm, (c) 2mm (d) 3mm and (e) 4mm.

Table 1. The 5th Natural Frequency of Beam with Different Crack Size.

Crack Size (mm)	5th Mode Frequency (Hz)
0	771.5
1	766.5
2	757.75
3	738.25
4	708.65

5. Conclusion

This paper presents a systematic procedure of the application of the experimental modal analysis as a SHM to evaluate the blade health condition. A simplified shape of the wind turbine blade (stepped beam) excited by impact hammer is used in this investigation. The modal parameters including modal frequency, modal shape and damping show valid parameters to monitor the condition of blade as they provide good correlation with fault size, therefore, these can be considered as a promising approach to detect and estimate the crack size. However, the damping ratio parameter is increased after introducing the fault and starts to reduce as the fault size developed, and may require further investigation and evaluation criteria before it is applied to blade faults diagnostics.

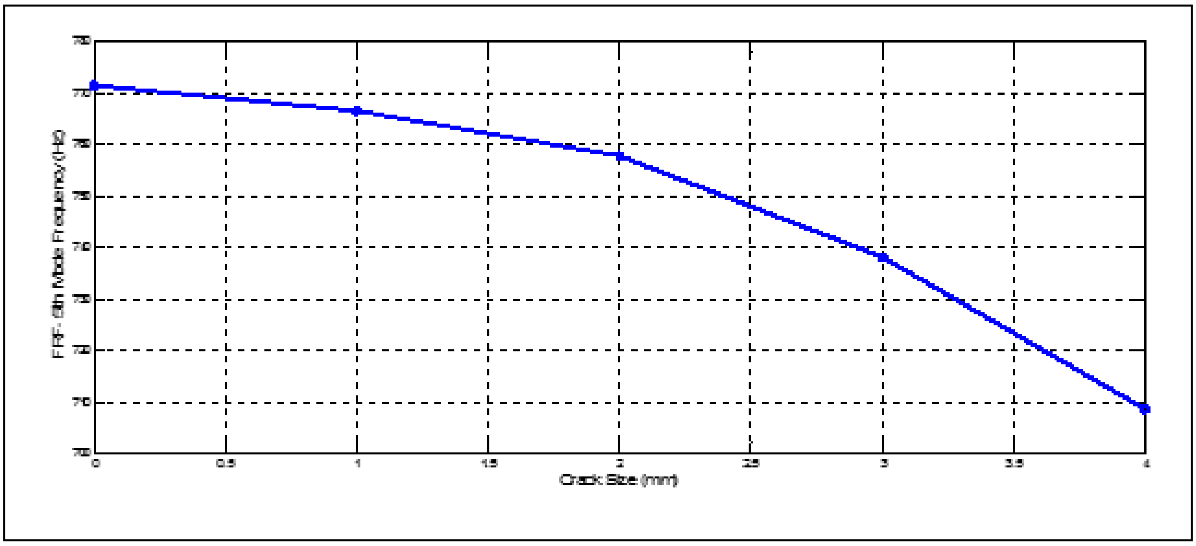

Fig. 7. The 5th FRF mode frequency with different fault size

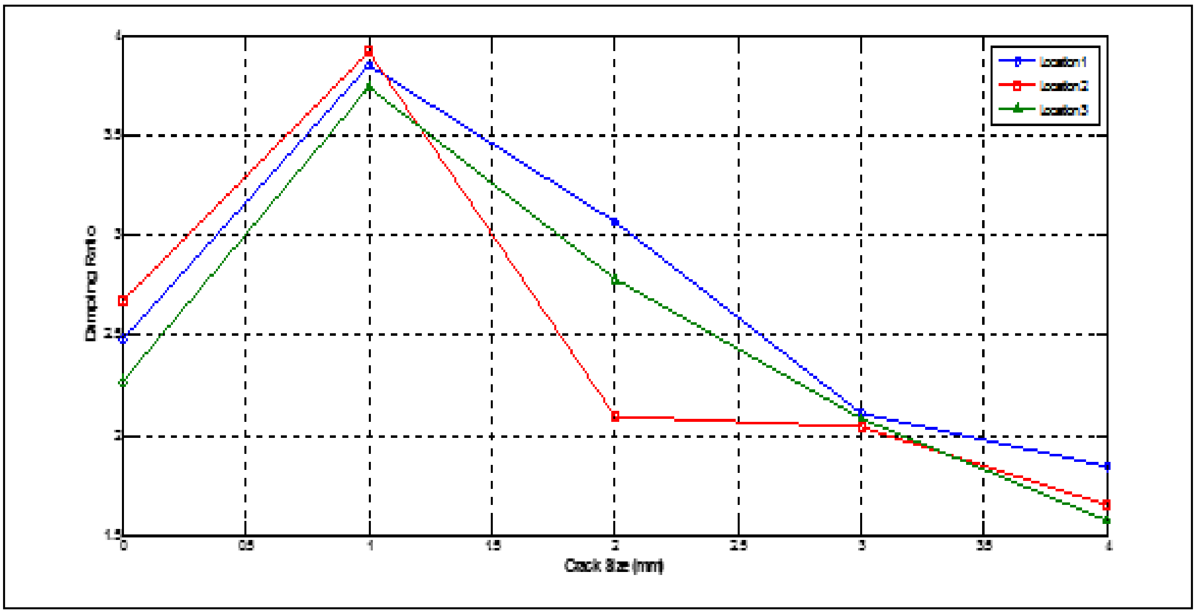

Fig. 9. The beam damping ratio with different crack size and impact location

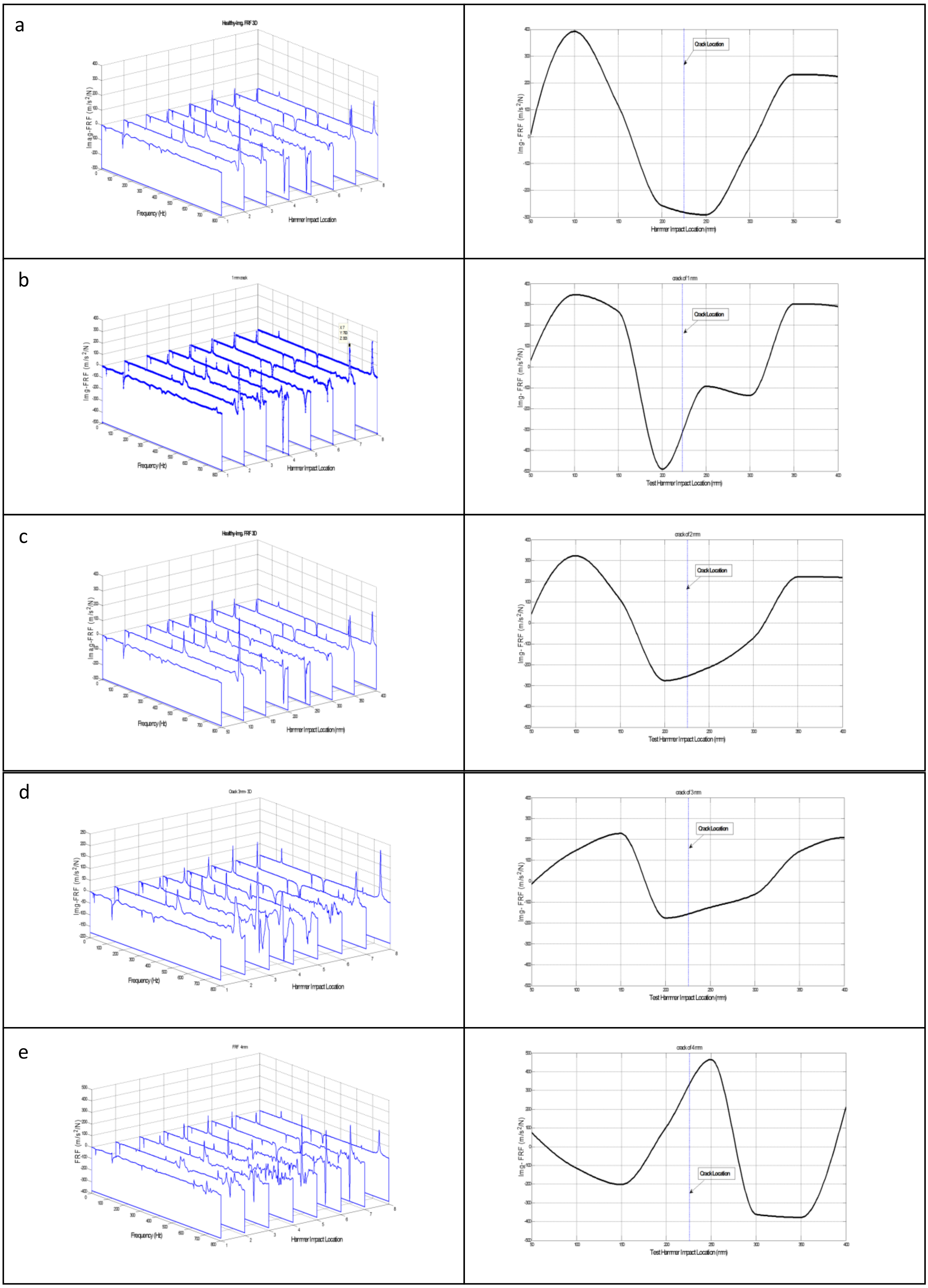

Fig. 8. the stepped beam modal shape with different crack size :(a) Healthy, (b) 1mm, (c) 2mm (d) 3mm and (e) 4mm.

Furthermore, it has been observed from the results that the variation of blade modal/ natural frequencies caused by introducing different crack conditions obtained from the experimental modal analysis in the current paper, shows a good consistency in comparison with the analytical finite element modal analysis developed using SOLIDWORK software by the authors in [3].

Acknowledgements

This is to acknowledge that this paper is a part of research project entitled “Automatic condition Monitoring and predictive diagnostics as applied to Wind Turbines” no. ORG/SU/14/010 funded by “The Research Council” (TRC) /Oman.

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