Jurnal
Teknologi

Full Paper

EFFECTIVENESS OF OPERATIONAL MODAL ANALYSIS (OMA) FOR DAMAGE DETECTION IN FIBERGLASS REINFORCED EPOXY

Article history
Received
22 February 2015
Received in revised form
30 April 2015
Accepted
31 May 2015

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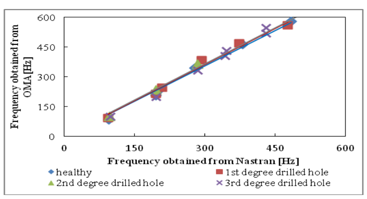
Graphical abstract



Abstract

This study attempts to apply vibration-based damage detection method specifically Operational Modal Analysis (OMA) on fiberglass reinforced epoxy plate. OMA is used on healthy fiber glass reinforced epoxy plate to extract the modal parameters and the procedure is extended to damaged fiberglass reinforced epoxy plate. Both healthy and damaged composite material are tested under different boundary conditions i.e. free-free on 4 edges, 1 edge clamped, 2 edges clamped, 3 edges clamped and 4 edges of free-free boundary condition. The result of frequency from OMA was compared analytically with Finite Element Method (FEM). Nastran software is employed in this study. The FEM using Nastran shows that the result obtained is not accurate enough compared to OMA. Therefore, another method was applied to look at the effectiveness of OMA method using Experimental Modal Analysis (EMA). It was observed that both EMA and OMA methods gave small deviation and good correlation.

Keywords: Composite materials, operational modal analysis, vibration based damage detection, frequency, finite element method

1.0 INTRODUCTION

Nondestructive evaluation (NDE) using damage detection based on vibration has becoming a recommended approach and received a lot of attention in engineering community for the last three decades [1]. This approach was done by comparing modal parameters of before and after the damaged was induced in structures. The modal parameters such as frequency, mode shape and modal damping are obtained from modal testing [2]. This approach can be called as feature extraction where a process of identifying damage properties is carry out by obtaining information from measured dynamic response [3]. This method can also be utilized by changes of its dynamic properties because modal parameters are functions of physical properties in structures [4]. From this fact, changes of physical properties will cause changes of modal properties. Therefore, this theory is improvised in damage detection based vibration.

Composite materials are classified by the geometry of reinforcement and by the type of matrix used [5]. Fiberglass reinforced epoxy was chosen to be the study case in this research. Fiberglass reinforced epoxy is one of Polymer Matrix Composites and it reinforcement type is fiber. It was chosen due to its vast advantages in engineering applications [6-8]. The advantages are reducing structural weight, low cost manufacturing, high strength and sample manufacturing principle.

Subsurface damage in composite materials such as matrix cracking, fiber breakage and delamination between plies are usually undetected in visual and localized experimental methods in most current NDT [9]. Current NDT is time consuming and costly. Moreover, most NDE methods need to know beforehand the vicinity of the damage and the inspected structure must be well accessible [10].The subsurface damages can only be detected and monitored by observing localized nonlinear vibrations. Therefore, Operational Modal Analysis (OMA) were implanted in this study to detect the subsurface damage by analyzing changes of frequencies, mode shapes and damping in healthy and damaged composite materials.

OMA or can also be called as ambient modal analysis, utilizes only measurement of a structures in operational condition to identify modal characteristics [11]. OMA was chosen due to its advantages. One of the advantages of OMA is able to perform model testing under operating condition without disturbing daily operation of machines or structures and without removing parts which is under testing. In addition, OMA capable to conduct cheap and fast vibration testing without using excitation equipment and boundary condition simulation. Furthermore, OMA also able to utilize all coordinates of measurement in the system as references therefore suitable for complex structures [11-12].

The purpose of this study is to validate the effectiveness of OMA method using Finite Element method (FEM) and Experimental Modal Analysis (EMA) by comparing frequency parameter. Nastran was used to validate OMA method. Meanwhile, EMA is one of modal analysis method beside OMA which is typically used in most modal testing.

2.0 RESEARCH METHODOLOGY

Basically, when performing OMA on fiberglass reinforced epoxy plate, there are four items need to be considered. They are forced excitation to vibrate the plate, transducer selection to measure signal from the vibrated plate, analyzer to measure vibration response from the accelerometer to establish magnitude of response and finally, preparation of test specimen which is the fiberglass reinforced epoxy plate.

OMA generally utilized ambient response to excite tested structures. However, forced excitation was carried out in this study due to this particular OMA experiment was done in controlled lab. Forced excitation was done by randomly tapping the plate using a pen so that sufficient energy was supplied to vibrate the healthy and damaged fiberglass reinforced epoxy plate.

Generally, piezoelectric transducer is widely used in most modal analysis applications. Moreover, there are two types of transducer which typically used in modal analysis practice. They are force transducer and accelerometer. However, accelerometer was selected in this research because this type of transducer able to measure output signal which was the vibration of tested plate produced by tapping using a pen. Furthermore, accelerometer was also selected due to OMA method only utilized output response of tested pen. This OMA method is differs with typical modal analysis which is normally utilized input response to measure vibration characteristic of a structure. The accelerometers used were an electromechanical transducer type, Delta Tron® Accelerometer with a sensitivity of 0.101V.Two accelerometers were used one which operate as reference and the other one was roved to each measurement points. It is important that the total weight of accelerometers used is one per tenth of the tested plate.

When performing modal analysis, analyzer was used to measure output response levels which developed by accelerometers to establish magnitude of responses. Pulse™ Bruel & Kjaer type 3560-D frontend type 30 channel analyzer was utilized to perform multiple analysis for noise and vibration. In addition, this analyzer able to concurrently analyze on the same and different channels while displaying real-time results on the screen. In this research, the first channel was connected to the reference channel while the second channel was connected to the roving channel.

(a) free-free boundary condition

(b) 1C3F,2C2F,3C3F,4C and 4F

Figure 1 Boundary condition experimental set-up for free-free and grounded conditions

Finally, when preparing test specimen, three items need to be considered. They are free and grounded support to hold the specimen, nodal layout of the specimen and the structural health condition of plate specimen itself which is healthy or damaged specimen. The fiberglass reinforced epoxy plate specimen was fabricated by molding and was cured for a minimum of eight hours.

Free and grounded support of the plate specimen is shown in Figure 1. Figure 1(a) shows the specimen was tested under free – free boundary condition (4F) and Figure 1(b) shows a clamping jig was used to simulate 1 edge clamped 3 edges free-free (1C3F), 2 edges clamped 2 edges free-free (2C2F), 3 edges clamped 1 edge free-free (3C1F) and 4 edges clamped (4C) boundary condition.

The nodal layout of the specimen was mapped on the surface to ensure accurate results have been taken. In this study, 42 points of measurement and node spacing was identified to locate the measurement points of the accelerometers. Point number 1 was set as reference point while the other 41 points were set as roving points.

To detect the structural health condition of the plate specimen, the plate specimen was prepared in four stages so that a progressive damage in this research can experimentally conducted. Healthy plate specimen was defined as plate with no drilled hole damage. 1st degree drill hole damaged specimen was defined as a hole with a diameter of 1cm. 2nd degree drill hole damaged specimen was defined as a hole with a diameter of 3cm. Finally, 3rd degree drill hole damaged specimen was defined as multiple holes induced in the plate specimen. Each of the specimens was tested under all boundary conditions using OMA method to obtained measured frequencies and mode shapes. Finally, the measured frequencies and simulated frequencies were compared to confirm the effectiveness of OMA method in detecting damage in fiberglass reinforced epoxy plate.

3.0 RESULTS AND DISCUSSION

3.1 Results Comparison Using FEM

The comparison between predicted frequencies and measured frequencies is discussed. The basis of comparison is done by comparing measured frequency and simulated frequency and this is the most obvious comparison technique when comparing modal properties [4,16,18]. The simulated frequencies were obtained using FEM through Nastran software. Basically, simulated frequencies were obtained by determining material and physical properties of fiberglass reinforced epoxy. However, actual frequencies were obtained by using OMA method. This is because only sufficient energy was used to excite the plate specimen and external noise presence during the experiment. Therefore, we try to generate analytical model but the result shows that the comparison between OMA and Nastran not accurate enough. To ensure OMA was correctly done, the result obtained from EMA is used to compare with the result obtained from OMA.

Validations of measured frequencies are shown as linear trend line graph as shown in Figure 2 and Figure 3. Each data set of measured frequencies was plotted against predicted frequencies of corresponding modes. Low degree of deviation between experimental and Nastran natural frequencies can be observed if the points are exact or close to the reference slope which represent by the dotted line.

Furthermore, Figure 2 shows result of specimen when tested under 4C boundary condition. Highest deviation can be observed at 2nd degree damaged specimen line. Although, low deviation can be observed when specimen tested at healthy, 1st degree drilled hole and 3rd degree drilled hole damaged lines.

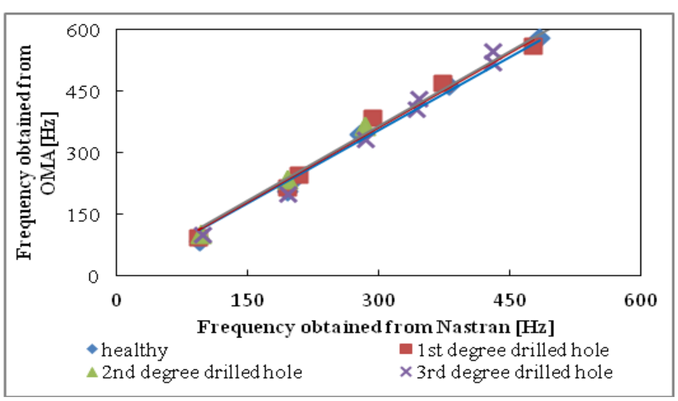


Figure 2 Drill hole damaged plate under 4C boundary condition

Frequencies simulated from Nastran do not agree with measured frequencies from OMA as can be seen in Figure 2 . Therefore, overall validation results show significant proportional systematic error [17] whereby at early modes from the range of 0 Hz to 200 Hz show points are near to the reference line (dotted line) but error between Nastran and OMA become more pronounce at higher modes. This error is due to material and physical properties of non homogeneous material exhibited from unidirectional of the fiber glass chopped in the specimens and bleed-out during curing. Therefore, material's elastic modulus, density, Poisson ratio and thickness could affect frequencies' value [13].

3.2 Results Validation Using Experimental Modal Analysis (EMA)

Figure 3 shows result of specimen tested at 3rd degree drilled hole condition and was set up experimentally under various boundary conditions which are 1C3F, 2C2F, 3C1F, 4C and 4F. Based on Figure 3, it was observed overall frequencies are close and mostly on the reference line (dotted line). This shows that identified frequencies extracted using OMA are accurate and can be validated experimentally by EMA. Therefore, validation using another modal analysis technique which is EMA demonstrated that OMA can be an effective modal extraction tools to obtained frequencies as one of vibration based damage detection parameters.

4.0 CONCLUSION

On the whole, the objective of this paper of this study was achieved. It was observed frequencies comparison between OMA and Nastran were not in good correlation. However, the results between OMA and EMA were found in good correlation.

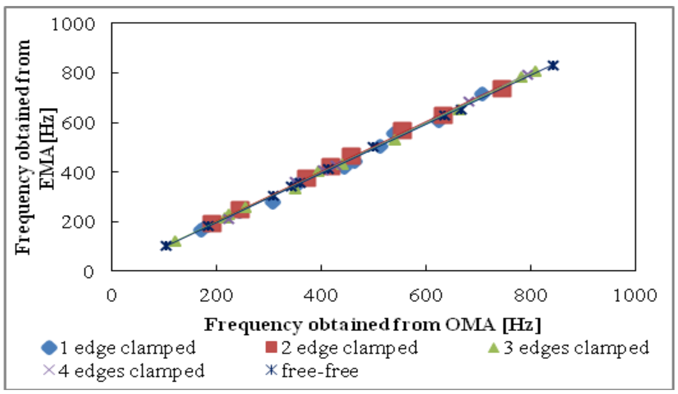


Figure 3 EMA against OMA at 3rd degree drilled hole damaged plate under all boundary conditions

Acknowledgement

The authors would like to acknowledge with appreciation to the support from Research Management Institute (RMI), Universiti Teknologi MARA(UiTM) and financial support from the Minister of Higher Education Malaysia(MOHE) for the grant of Research Acculturation Grant Scheme (RAGS).

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