Time Effective Structural Frequency Response Testing with Oblique Impact

Khoo Shin Yee, Lian Yee Cheng, Ong Zhi Chao, Zubaidah Ismail, Siamak Noroozi

Abstract**—**Structural frequency response testing is accurate in identifying the dynamic characteristic of a machinery structure. In practical perspective, conventional structural frequency response testing such as experimental modal analysis with impulse technique (also known as "impulse testing") has limitation especially on its long acquisition time. The high acquisition time is mainly due to the redundancy procedure where the engineer has to repeatedly perform the test in 3 directions, namely the axial-, horizontal- and vertical-axis, in order to comprehensively define the dynamic behavior of a 3D structure. This is unfavorable to numerous industries where the downtime cost is high. This study proposes to reduce the testing time by using oblique impact. Theoretically, a single oblique impact can induce significant vibration responses and vibration modes in all the 3 directions. Hence, the acquisition time with the implementation of the oblique impulse technique can be reduced by a factor of three (i.e. for a 3D dynamic system). This study initiates an experimental investigation of impulse testing with oblique excitation. A motor-driven test rig has been used for the testing purpose. Its dynamic characteristic has been identified using the impulse testing with the conventional normal impact and the proposed oblique impact respectively. The results show that the proposed oblique impulse testing is able to obtain all the desired natural frequencies in all 3 directions and thus providing a feasible solution for a fast and time effective way of conducting the impulse testing.

Keywords**—**Frequency response function, impact testing, modal analysis, oblique angle, oblique impact.

I. Introduction

STRUCTURAL frequency response testing with impact testing is commonly used to identify the dynamic characteristics of a machinery structure. This testing is also known as "experimental modal analysis (EMA)" [1]. It has been implemented in a wide range of field for the purpose of testing, design, and development of a new product/system. Dynamic information such as the natural frequency, modal damping and mode shape are used in solving the vibration problem, fatigue & damage problem and inverse identification problem. However, conventional EMA has a limitation in the data acquisition process where it requires the machine to be shut down completely [2]. Moreover, to comprehensively understand the dynamic behavior of a 3D structure, there is a need to conduct multi-reference EMA that repeatedly perform the impact testing in 3 principal directions, namely the axial-, horizontal- and vertical-axis [3]. Therefore, the high testing time of multi-reference EMA is not favorable in many industries. For example, the cost of downtime and unscheduled shutdown can be as high as USD 100,000 per day in the petrochemical industry [4]. Therefore, there is a need to reduce the testing time to save the maintenance cost.

This study initiates an experimental investigation of impulse testing with oblique impact, i.e. the impact is excited to the structure at oblique or non-normal angle. The intention of imposing an oblique impact instead of normal impact is to induce a significant vibration response in all the 3 directions simultaneously. With that, the vibration modes at 3 directions can be obtained by using signal processing technique. Hence, it is expected that the acquisition time can be reduced by a factor of three by using the proposed method.

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II. Theory

A. Structural Frequency Response Testing with Normal Impact

Structural frequency response testing with impulse technique is frequently used to measure the dynamic characteristic of a system such as natural frequency, damping and mode shape [1]. This technique requires a complete 'shut down' situation of the system with no unaccounted excitation force. Theoretically, if the impact force and the corresponding vibration can be measured, the structural frequency response function (FRF) can be obtained, as in (1):

$$H_{ni:nj} = \frac{\ddot{X}_{ni}}{F_{nj}} \quad (1)$$

where $H_{ni:nj}$ is the FRF or the transfer function due to force, F acting at location n and direction j and its corresponding acceleration response, $\ddot{X}$ measured at location n and direction i.

To perform the impulse testing, the reference DOF of the force must be normal to the surface of a 3D structure, denoted as x-, y-, & z- axis respectively. A complete FRF matrix can be obtained, as in (2):

$$\begin{bmatrix} H_{1x:1x} & H_{1x:1y} & H_{1x:1z} & \cdots & H_{1x:nj} \\ H_{1y:1x} & H_{1y:1y} & H_{1y:1z} & \cdots & H_{1y:nj} \\ H_{1z:1x} & H_{1z:1y} & H_{1z:1z} & \cdots & H_{1z:nj} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ H_{ni:1x} & H_{ni:1y} & H_{ni:1z} & \cdots & H_{ni:nj} \end{bmatrix} = \begin{bmatrix} \ddot{X}_{1x} \\ \ddot{X}_{1y} \\ \ddot{X}_{1z} \\ \vdots \\ \ddot{X}_{ni} \end{bmatrix} \begin{bmatrix} F_{1x} \\ F_{1y} \\ F_{1z} \\ \vdots \\ F_{nj} \end{bmatrix}^{-1} \quad (2)$$

Instead of measuring a complete FRF matrix, a single column or single row of FRF matrix is able to obtain the modal parameters of dynamic characteristics at particular direction [5]. Thus, a minimum 3 sets of single column/row FRF are needed to acquire vibration modes at all the three translational directions. However, the redundancy procedure is time consuming, especially conducting testing for a large structure where a large number of measurement points are needed. Therefore, structural frequency response testing with oblique impact is proposed in this study to reduce the time consuming testing process.

B. Structural Frequency Response Testing with Oblique Impact

The schematic diagram of the oblique impact and normal impact is shown in Fig. 1.

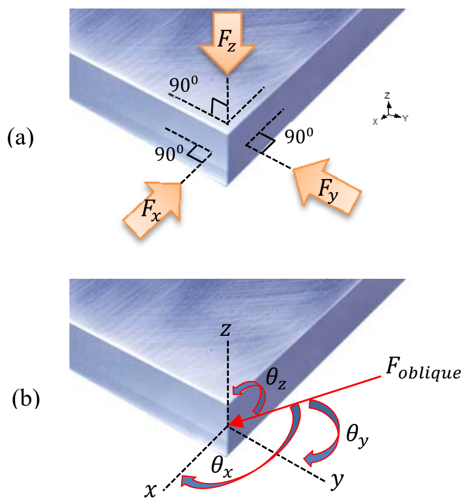

Fig. 1 (a) Normal impact $(F_x, F_{1y}, \& F_{1z})$ and (b) oblique impact $(F_{oblique})$ acting on a plate

Theoretically, if we introduce an oblique impact on a structure, the oblique force, $F_{oblique}$ can be transformed to 3 principal coordinates, as in (3):

$$\begin{aligned} F_x &= F_{oblique} cos\theta_x \\ F_y &= F_{oblique} cos\theta_y \\ F_z &= F_{oblique} cos\theta_z \end{aligned} \quad (3)$$

where θ_x , θ_y, and θ_z are the angles between the oblique force and the x-, y-, & z- axis respectively. In other words, a single oblique impact can represent 3 normal forces acting on the structure simultaneously. With that, we would be able to obtain the vibration modes at 3 normal directions simultaneously, as the oblique force will result response that is contributed by vibration modes in x-, y-, & z- axis.

III. Materials and Methods

A. Set-up of Experiment Equipment

A T-shaped Aluminium plate consisted of a motor coupled to rotor shaft is used as the test rig in this study, as shown in Fig. 2. A tri-axis accelerometer is used to measure the 3D translational vibration of the plate at 19 locations. A modally tuned impact hammer was used to record the time history of the impact force. The vibration and force signals were acquired by a data acquisition (DAQ) system and the data was transferred to a laptop. Hence, post-processing of the data can be proceeded by using DASYLab® and MESCOPE® software.

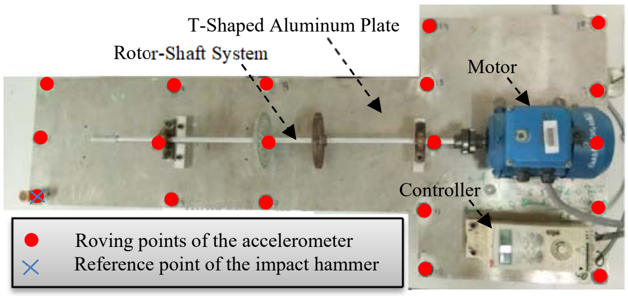

Fig. 2 Motor-driven test rig

B. Procedure

Single Input Single Output (SISO) approach by using a roving accelerometer and a reference impact hammer was implemented to acquire the data. The reference point is chosen at the anti-node point of the vibration modes within 50 Hz, as this is the frequency of interest (i.e. based on the maximum operating frequency of the motor – 50 Hz). A total of 19 measurements was taken at 19 locations by using tri-axis accelerometer for the EMA with normal impact acting at x-, y-, & z- axis and the EMA with oblique impact respectively. The oblique angles used in the testing are given as follow: $\theta_x = 60^0$, $\theta_y = 60^0, and\ \theta_z = 45^0$. All the force and response data were acquired by using DASYLab® software.

A total of 50 averages are used to reduce the measurement noise. Sampling rate (2048 Hz) and block size (4096 samples) of the FRF measurement are set to obtain time and frequency resolutions of 0.000488 s and 0.5 Hz respectively. By post-processing the data in DASYLab® software, the FRF due to normal force acting at x-, y-, & z- axis as well as the FRF due to oblique force can be obtained, as follows (1). Thus, the vibration modes at 3 principal modes can be curve fitted in MESCOPE® software, in order to obtain the modal parameters. The modal parameter results obtained from the EMA with normal force and oblique force will be compared and the result is reported and discussed in the next section.

IV. Result and Discussion

The FRF measurement results due to the normal impacts at x-, y-, & z- axis respectively are plotted in Fig. 3. The FRF

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measurement results due to the oblique impact ($\theta_x = 60^0$, $\theta_y = 60^0, and\ \theta_z = 45^0$) are plotted in Fig. 4.

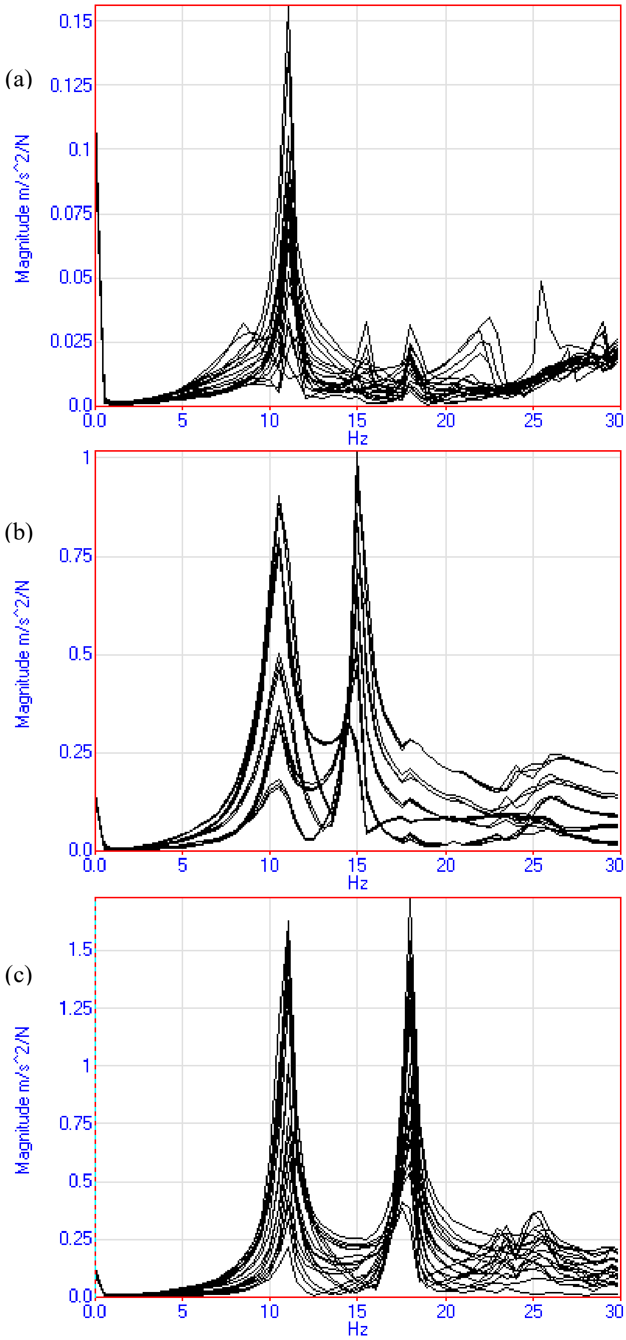

Fig. 3 FRF measurement result due to normal impact at (a) x-axis, (b) y-axis, and (c) z- axis

Fig. 3 shows that the FRF due to normal impact consists of 3 vibration modes at 3 different frequencies across the x-, y-, & z-axis. A similar result is obtained for the FRF due to oblique impact, as shown in Fig. 4. Note that the peak of the FRF indicates the natural frequency of the test rig.

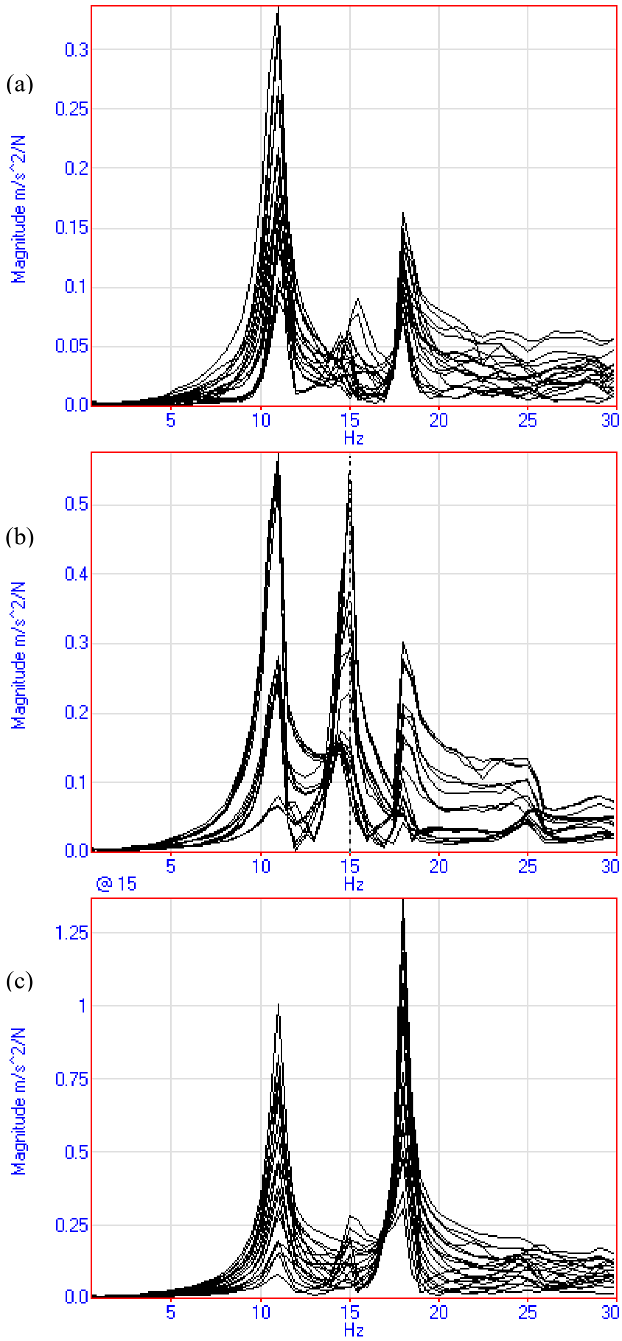

Fig. 4 FRF measurement result due to normal impact at (a) x-axis, (b) y-axis, and (c) z- axis

The overlaid results of FRF measurement due to normal force and oblique force are shown in Fig. 5. It clearly shows that proposed FRF measurement with oblique impact method is able to extract all the natural frequencies, as compared to the conventional FRF measurement result with normal impact. Both FRF measurement results contain 3 similar natural frequencies (i.e. frequencies at the peaks of the FRF magnitude).

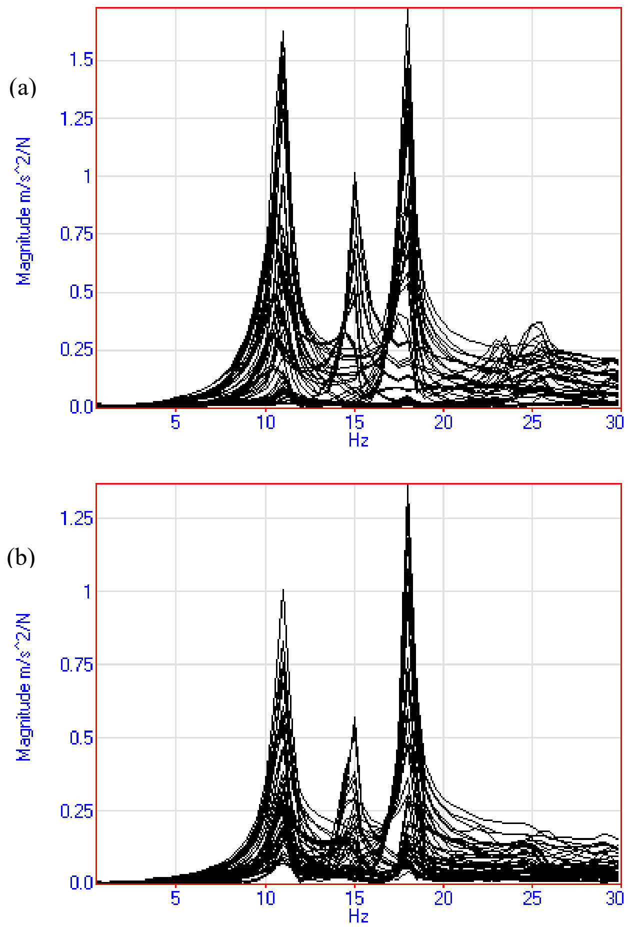

Fig. 5 Overlaid results of FRF measurement due to (a) normal impact and (b) oblique impact

TABLE I
NATURAL FREQUENCY RESULTS FOR EMA WITH OBLIQUE IMPACT AND NORMAL IMPACT

Vibration Mode	EMA with oblique impact (Hz)	EMA with normal impact (Hz)	Difference in Natural Frequency (%)
Mode 1	11.0	11.0	0.00
Mode 2	14.8	15.0	1.33
Mode 3	18.1	17.9	1.12

Next, the modal parameters can be extracted by using the curve fitting algorithm in MESCOPE® software. The natural frequencies for the EMA with normal forces and oblique force are given in Table I. Table I shows that the accuracy of the EMA with the proposed oblique impact method achieves 100%, 98.67%, and 98.88% for mode 1, 2, and 3 respectively. However, the comparison between the mode shape is not available in this study. This is because multi-reference curve fitting of the FRFs with 3 reference normal impacts will generate 3 sets mode shapes while single-reference curve fitting of the FRFs with 1 reference oblique impact will generate 1 set mode shape only. Despite that, the results show the great potential of the proposed oblique impact in enhancing and promoting the time effective structural frequency response testing instead of applying 3 repeated normal forces.

V. CONCLUSION

A time effective structural frequency response testing with oblique impact is successfully investigated in this study, where this proposed method able to reduce the testing time by a factor of 3 times. The accuracy of the measured natural frequencies using the oblique impact is more than 98.88%, as compared to the conventional normal impact method. Comparison of mode shape is not available in current study due to the limitation of the curve fitting and this should be improved in the future work. Also, it is suggested to determine the optimum oblique angle in future, in order to enhance the modal parameter extraction results.

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