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Finite element analysis validation of a novel experimental modal analysis method

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Abstract
In this paper, we propose and validate an approach using Experimental Modal Analysis (EMA) based on Frequency Response Function (FRF) for machine vibration analysis. The EMA utilizes a set of accelerometers as vibration sensors to gather vibration measurements at selected locations on the machine, from which the relative sensitivities are computed to yield a sensitivity map. This sensitivity map is useful to examine the vibration behaviour of the mechanical structure and determine the final placement of monitoring sensors. The proposed approach is evaluated and benchmarked with Finite Element Analysis (FEA) model.

Keywords: Vibration sensitivity measurement, experimental modal analysis, frequency response function, finite element analysis, optimal sensor placement, real-time condition monitoring.

1. Introduction

Modal analysis is one of the possible procedures under vibration analysis to quantify the behaviour of a mechanical structure. Modal analysis uses modal parameters such as modal frequency, sensitivity, damping ratio of a mechanical system to formulate a mathematical model for its dynamic behaviour. Such method is well established and commonly used for a Linear Time Invariant (LTI) system [1].

Theoretical modal analysis relies on the description of physical properties of a system to derive an accurate model [2]. However, the experimental modal analysis (EMA) proposed by Kennedy in 1947 obviates the need for such a model [3]. The procedure of EMA can be conducted via a number of vibration sensors attached to the mechanical structure of a machine with the vibration source naturally present into the structure. The time data collected from the sensor will be transformed into the frequency domain using Fast Fourier Transform (FFT) and further computed and analysed using the Frequency Response Function (FRF). FRF is a method to measure the ratio of the output response of a structure due to an applied excitation source with different excitation frequencies. The theoretical basis of this technique is to establish the relationship between the vibration response at one location of interest. Such response can be measured in term of acceleration, velocity, or displacement. The modal frequencies and damping can also be obtained from these measurements. With the modal frequency available, the deformation pattern of the structure can be observed and subsequently the ideal location for sensor placement can be identified.

In this paper, an approach based on EMA will be presented to capture the vibration characteristic of a machine. A typical drilling machine is used to illustrate the proposed idea. One possible scenario the drilling machine is facing is the gradual degradation of the cutting tool. A worn out cutting tool will produce unwanted vibration during machining operation and subsequently affects the machining output quality. Therefore, the vibration spectrum at the cutting tool tip should be closely monitored. It is well-known that the cutting tool tip is not a place to mount any sensors for direct measurements as it directly engaged the work piece during machining process. Hence, sensors should be placed at other locations on the machine to make the condition monitoring at the tool tip becomes feasible. The proposed approach is then compared and benchmarked with Finite Element Analysis (FEA) performance.

2. Proposed approach

The key objective to be addressed in this paper is to determine the relationship between the vibration at the reference point V_r (tool tip) and the possible sensor mounting locations V_i on a machine. This relationship can be derived from the sensitivity equation, s_{ij} which measures how sensitive a sensor location able to pick up the vibration at the reference point given the same frequency of interest [4].

$$s_{ij} = \frac{a_{ij}}{a_{rj}} \tag{1}$$

where $i: 1 \rightarrow n$ is the multiple sensor placement locations, s_{ij} is the vibration sensitivity, a_{ij} and a_{rj} are the amplitudes of the vibration measurements at V_i and V_r at frequency ω_j respectively.

The computed vibration sensitivities data can be represented in a matrix form representing the machine mechanical structure as shown in Equation (2) by repeated the step over $j: 1 \rightarrow m$ discrete frequencies. A graphical geometry plot representing sensitivity map from S combined with geometry coordinates (x, y) of sensor location and its sensitivity can constructed.

$$S = \begin{pmatrix} s_{11} & \cdots & s_{n1} \\ \vdots & \ddots & \vdots \\ s_{1m} & \cdots & s_{nm} \end{pmatrix} \qquad (2)$$

3. Experiment results and discussion

3.1. Experiment setup

Figure 1 shows the experiment setup: (1) the test fixture that emulates a drilling machine, (2) a vibration motor controlled to produce $120Hz$ operating frequency, is attached to the emulated drilling machine in-order to simulate the vibration generated from a worn-out drill bit (cutting tool), (3) accelerometers are used to measure the vibration at the cutting tool and sensor placement locations on the test fixture.

3.2. EMA analysis

The 3D sensitivity map in Figure 2 shows geometrically and graphically the sensitivities distribution over the defined part of the machine structure. The sensitivity map can be used to identify the sensor placement for condition monitoring as the most sensitive locations are easily identified from the graph. From the 3D sensitivity map, The locations (7,1) and (8,1) labelled on the test fixture are identified as the most sensitive locations for dominant frequency of $120Hz$. The other sensor locations are less sensitive could be due to the rigidness of the test fixture as different tightness may be applied to the fixed supports (screws) that secure the test fixture on the machine.

3.3. FEA benchmark

FEA is highly dependent on the model of a machine which encompasses the geometry information, material decomposition and even the assembly tolerances of the constituent components. It is a known challenge to model a machine in all aspects to a high level of accuracy in order to obtain a precise analysis result. Figure 1 is transformed into a mechanical drawing in order to run the FEA simulation. In FEA modal analysis, the input parameters (FEA modelling) include material properties such as Young's modulus and density, assembly tolerances, designated fixed supports of the structure, direction and magnitude of the vibration motor when it is in operation. These input parameters for simulation are based on authors' best knowledge towards describing the actual system. Figure 3 shows the sensitivities distribution done in FEA analysis where sensor locations (1,5), (7,1), (8,1) and (8,2) are the highly sensitive locations. Among all the identified locations, (7,1) and (8,1) matched with the EMA analysis. The FEA simulation is based on the condition where the FEA modeling is assumed to be correct. A slightly mismatched in the FEA modeling will gives inaccurate simulation results. Hence, the input parametric values need to be properly calibrated in order to achieve a close match between simulation and experimental results.

4. Conclusion

The main challenge in using FEA is to get a highly precise model in order to obtain an accurate result for the machine structure analysis. This method is extremely difficult especially to those large scale and complex precision machine. By not using the FEA approach, a method for machine structure analysis based on EMA and FRF is proposed. Without the needs of knowing an accurate machine model, this approach makes use of a series of vibration sensors mounted at the reference and other sensor placement locations for vibration sensitivity measurement. The top ranked vibration sensitivity location is then being selected as the final sensor placement site for machine condition monitoring. The effectiveness of the proposed method is validated and benchmarked against FEA.

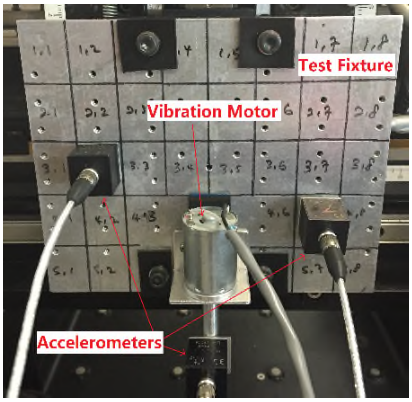

Figure 1. Experiment setup

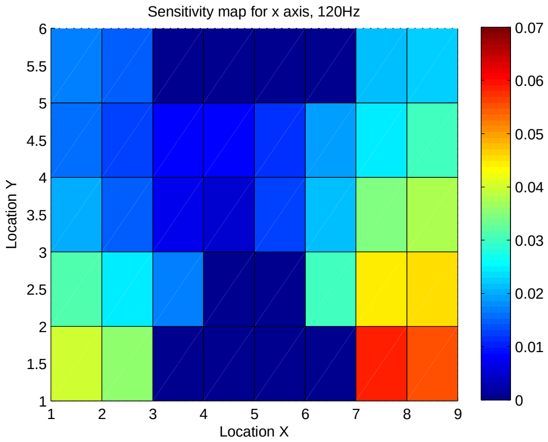

Figure 2. EMA sensitivity map

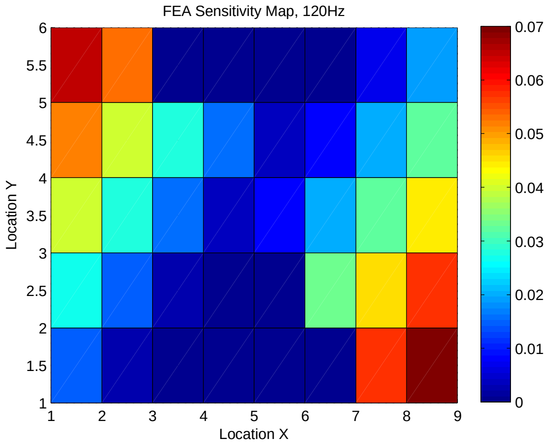

Figure 3. FEA sensitivity map

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