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A Simplified Technique to Distinguish Unbalance and Misalignment using Frequency Domain Operating Deflection Shape

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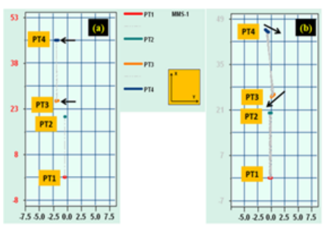
Graphical abstract



Abstract

Machinery fault can be identified by performing Condition-Based Monitoring (CBM) program which rely on the machinery vibration data. However, the data which represented by the time wave and vibration spectrum requires technically trained personnel to understand and diagnose. In this research, a simplified technique through visualization of the Operating Deflection Shape (ODS) is proposed. The technique combines both the data of vibration amplitude and phase measurement. An ODS of a general machinery arrangement can be visualized from 4 measurement points. The technique is performed and tested in laboratory condition. Future CBM program should implement this technique because it helps untrained personnel to be able to distinguish primary machinery fault such as unbalance and misalignment easily by visualizing the machine motion.

Keywords: Fault diagnostic, operating deflection shapes (ODS), condition-based monitoring (CBM), phase, unbalance, misalignment

1.0 INTRODUCTION

A continuous operation is very crucial since it is the mechanism for any business to gain profit. A properly planned maintenance work is important to ensure the operation is not interrupted by any machinery failure. Because of this, Condition-Based Monitoring (CBM) program is considered as the best maintenance program which can monitor the machines condition while in operation and at the same time can detect machinery fault [1, 2]. This will help maintenance personnel to plan for maintenance work and reduce downtime.

Despite the advantages, lack of skilled and trained personnel can cause unsuccessful CBM program. Conventional machinery fault diagnostic technique only interprets the vibration signal by examining every single spectrum. The spectrum consists of certain frequencies component which match with certain machine parts (such as bearing, gear and impeller) or certain machine fault (such as unbalance and misalignment). Phase measurement is an important data that should be included in machinery fault diagnostic. Conventionally, phase measurement was acquired by using a tachometer which requires a machine to be shutdown. In this research, two accelerometers will be used with one unit assigned as the reference to get the phase measurement. This technique can acquire the phase data without any interruption on the machine operation [3].

This research is focusing on the primary machinery problem which is rotor unbalance and misalignment. Rotor unbalance and misalignment are the primary problem for most machines which cause secondary damage such as bearing failure, worn out gear, damaged impeller etc. [4]. Conventionally, rotor unbalance and misalignment problem can be detected from vibration spectrums. However, a research found that vibration spectrum analysis did not provide a good, reliable tool for detecting rotor unbalance and misalignment. There were some cases where unbalance and misalignment are producing the same vibration characteristic, which may lead to false data interpretation and diagnosis [5, 6,]. Another alternative to detect rotor unbalance and misalignment was proposed by using time domain Operating Deflection Shapes (ODS) [7, 8].

The ODS analysis can be performed either in frequency domain or time domain. ODS analysis is a measurement technique of determining the motion of a machine while it is in operation. The motion of a machine in actual condition at certain frequencies can be obtained from ODS analysis and helps the personnel to determine the cause of the motion using some digital signal processing technique [9, 10].

Time domain ODS is ideal for analyzing signals that are not steady-state (constant speed). A number of accelerometers and a lot of analyzer channels are required to perform time domain ODS which is not practical to be implemented in CBM program [11].

Frequency domain ODS utilizes at least two accelerometers to measure vibration signal, one of the accelerometers remains fixed while the other unit is roving on the selected points on the machine. The relation of the amplitude and phase was calculated for each of the roving accelerometer locations with respect to the fixed accelerometer. So far, no research had been done to implement the frequency domain ODS technique into CBM program.

Instead of analyzing every single spectrum, this technique can eventually help untrained personnel to distinguish major machines fault (such as unbalance and misalignment) easier and detect abnormal vibration earlier through visualization of the ODS.

2.0 BACKGROUND THEORY

The fundamental for the background theory of this research had been established by previous researches. In this research, the system was in a steady-state operating condition, and can show full 3D motion (ODS motion was developed using DASYLab® software). During the roving accelerometer process, it was crucial to ensure that running speed remain constant. In this research, the effect of random noise in the signal was reduced by performing synchronized averaging [12].

An ODS depends on the applied forces/loads. Therefore the forced vibration response of a linear structure for a general system [13] can be expressed as follows:

$$[M]\{\ddot{X}(t)\}+[C]\{\dot{X}(t)\}+[K]\{X(t)\}=[F](t) \quad \text{(Eq. 1)}$$

Or equivalent

$$[M]\{\Phi\ddot{X}_p(t)\}+[C]\{\Phi\dot{X}_p(t)\}+[K]\{\Phi X_p(t)\} = [F](t) \quad \text{(Eq. 2)}$$

Where x = ΦX_p (t) is the forced response, [M] is the mass matrix, [C] = α [M]+ β[K] is the damping matrix, [F](t) is the excitation force vector and is the modal matrix representing the mode shape vectors. Writing equation (2) as a decoupled system, equation (2) can be written as follows:

$$[\bar{I}]\{\ddot{X}_p(t)\}+[2\sigma_r]\{\dot{X}_p(t)\}+[\omega_r^2]\{X_p(t)\} = [\Phi]^T[F](t) \quad \text{(Eq. 3)}$$

Where $[\bar{I}]$, $[2\sigma_r]$ and $[\omega_r^2]$ represents diagonal matrices of elements; $\bar{I}$ is the identity matrix, ω_r is the eigenvalue of mode r, σ_r is the decay rate, and Φ_r is the normalized mode shape or the eigenvector of the mode r. For a system which subjected to a harmonic excitation with harmonic force define by $\{F\} = \{f\}e^{i\omega t}$, a solution form can be derived as $\{x\} = \{X(t)\}$ where ω is the excitation frequency, *t* is the time and X(ω) is the location amplitude vector defined as:

$$\{X(\omega)\}=\sum\frac{\{\Phi\}_r\{\Phi\}_r^T\{F\}}{\omega_r^2-\omega^2+2\sigma_r\omega i} \quad \text{(Eq. 4)}$$

Which represent the ODS of the system subject to a harmonic excitation.

3.0 METHODOLOGY

Laboratory rotor kit is fabricated which consists of a variable speed motor, balancing disc, roller bearing, and rubber type coupling. Two measurement points are on the motor side (drive end and non-drive end) and another two measurement points are on each roller bearing. Where point 1 is driver Non-Drive End (NDE), point 2 is driver Drive End (DE), point 3 is driven DE and point 4 is driven NDE. Additional mass is added on the balancing disc to simulate the static unbalance and dynamic unbalance. The coupling is misaligned horizontally to simulate the parallel and angular misalignment behavior.

Conventionally, trained personnel used a tachometer for additional phase measurement data. The method need to interrupt the operation before it can be performed. However this practice takes long time in machinery diagnostic as user needs to screen through the entire measured spectrum one by one. To improve this, integrating of phase data into current machinery fault diagnostic technique is proposed, namely 4-point ODS technique.

The laboratory rotor kit is operating at 25Hz (1500rpm). A normal vibration data is acquired by the 4-point ODS as the baseline at all 4 measurement points. 4-point ODS is performed for every simulated fault conditions. As a result, each set of measurement consist of 12 spectrums for all 4 measurement points in 3 different directions (axial, horizontal, and vertical). The spectrums are overlaid in single plot so that user can easily select the specific frequency.

4.0 RESULT AND DISCUSSION

Rotor unbalance is always related to a spectrum with dominant 1 time running speed. For machine which is having a static unbalance and dynamic unbalance conditions respectively, user unable to identify the type of unbalance by relying on the spectrum only. This example demonstrates the difficulty faced by CBM personnel. The ODS for static and dynamic unbalance can be visualized by putting the cursor on 1 time running speed. The 4-point ODS as shown in Figure 1 enable personnel to visualize the motion of the machine. Figure 1(a) shows point 3 and point 4 are moving in same direction which is in phase. This measurement is categorized as static unbalance. While Figure 1(b) shows point 3 and point 4 is moving in different direction which is out of phase. This is known as dynamic unbalance.

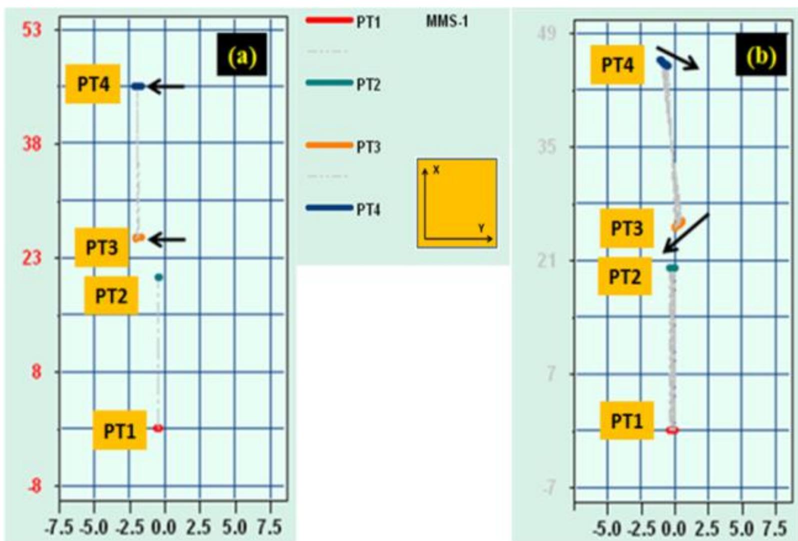


Figure 1 ODS of (a) Static unbalance (b) Dynamic unbalance

Spectrum with multiple harmonics usually related to looseness problem. Without considering phase data, the interpretation may lead to false machinery diagnosis. The competence of the 4-point ODS is examined in this case. The ODS for parallel and angular misalignments are showed by using magnitude and phase data at 2 times running speed. The result of 4-point ODS is shown in Figure 2. Personnel can easily visualize and distinguish the difference between both misalignments. This example demonstrates that personnel can easily identify and differentiate the machine problem with 4-point ODS. Figure 2(a) shows point 2 and point 3 are moving in different direction which is horizontally out of phase. This indicates the parallel misalignment problem. While Figure 2(b) shows point 2 and point 3 are moving in different direction which is axially out of phase. This is an indication of angular misalignment problem.

Phase measurement is important to distinguish machinery faults. However, current CBM practice only uses it for further analysis once a problematic machine occurs. Future CBM program should implement the 4-point ODS technique as a routine program. All vibration and phase data should be acquired during the scheduled monitoring program without any interruption on the operation process.

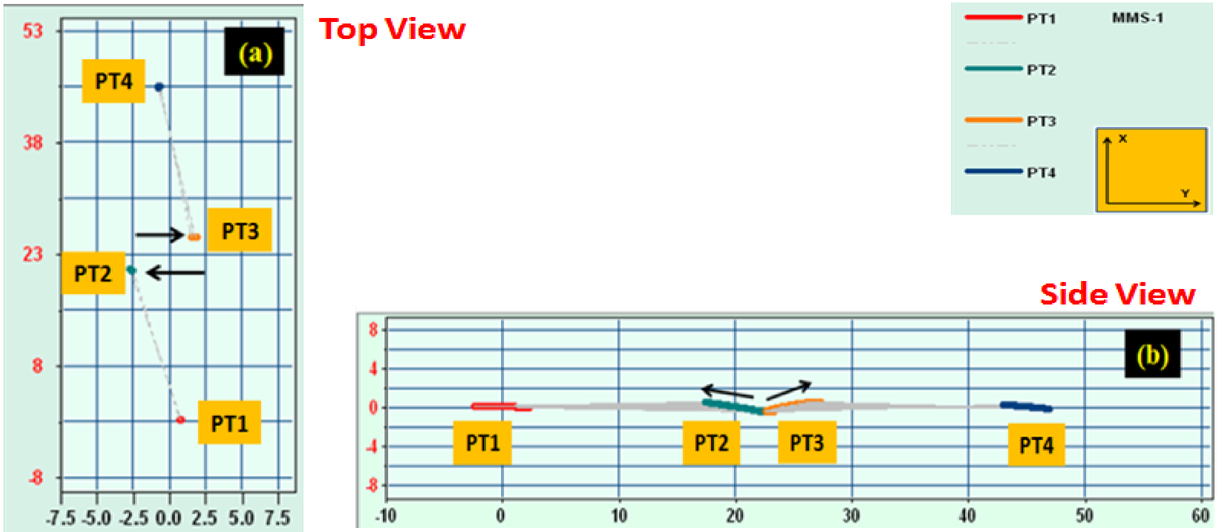


Figure 2 ODS of (a) Parallel misalignment (b) Angular misalignment

4.0 CONCLUSION

In this research, the 4-point ODS shows that unbalance and misalignment can be distinguished easily through visualization. Phase measurement is crucial and should be implemented into current machinery fault diagnostic technique which relies on spectrum only. From the 4-point ODS motion, personnel can visualize the deflection shape of the machine. Therefore, primary machine problem such as unbalance and misalignment can be detected earlier and easier without analyzing every single spectrum. Future upgraded version of vibration analyzer should consider this technique to ensure more accurate fault diagnosis and eliminate primary problem such as unbalance and misalignment easier. Furthermore, an untrained personnel are able to understand the behavior of the machine through 4-point ODS.

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