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Non-Destructive Testing and Diagnostic of Rotating Machinery Faults in Petrochemical Processing Plant

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Abstract. Machinery fault detection as part of predictive maintenance based on the machine vibration has been practiced comprehensively in oil and gas industry and power generation plant for maintaining the reliability of the machineries. Despite the advantages, the efforts of identifying machinery fault earlier may lead to inaccurate interpretation and diagnosis due to lack of knowledge, skill and experience. Conventional vibration data acquisition and analysis using single axis accelerometer are time consuming. Therefore, an approach which relies on the visualisation of machine vibration motion technique is proposed. The visualisation of machine vibration motion was performed through a simplified Operating Deflection Shape (ODS) analysis. ODS analysis on a 4 measurement points is enough to show the motion of general machinery arrangement which consist of 2 bearings on the drive side and another 2 bearings on the driven side. The effectiveness of the simplified technique was tested in a laboratory condition before being applied in oil and gas industry. The results show vibration data acquisition is more efficient and time saving by using tri-axis accelerometer and relative phase technique. Furthermore, machinery fault diagnosis can be identified easily, faster and more accurate through visualising the machine vibration motion using a simplified 4- point ODS. This simplified technique is seen as practical approach to be proposed and integrated into conventional machinery fault detection and predictive maintenance based on the machine vibration.

1. Introduction

Vibration is defined as a movement in rotational, swinging or linear direction. Most machines in operation produce certain amount of vibration affecting the associated components and systems including pipelines and pipe systems. The systems are of great importance in many industries such as water supply, oil and gas, and nuclear power generating. Structural reliability of structural systems such as beams and beam-like structures, frame structures, and bridges can be affected by vibration and has to be continually inspected [1–3]. Liu and Kleiner [4] have reviewed the state-of-the-art of inspection techniques and technologies towards condition assessment of water distribution and transmission mains. Research works of fault diagnosis on structural systems and machinery fault were also been studied [5,6]. After a continuous run, a machine and its associated systems will have their downtime due to the fatigue and malfunction of its critical parts. Failure of the systems has to be avoided since it can have disastrous effects, leading to injuries and fatalities, as well as substantial cost to industry and the environment [7,8]. Therefore, it is very crucial to perform maintenance activity to ensure the continuation of the machine operation.

General machinery maintenance can be categorised into three which are breakdown maintenance, scheduled (preventive) maintenance, and predictive maintenance. Oil and gas industry and power generation plant are two sectors that comprehensively conducting predictive maintenance on maintaining machinery reliability. Predictive maintenance program can predict developing problems before failure and damage can occur by trending and analysing the machinery vibration. The most desirable way to maintain machinery condition is by performing the inspection while machine under operation. Early detection of minor defects and machine failure characteristic can be identified while the machine runs and it will not affect the operation performance [9].

Despite the advantages of predictive maintenance program, conventional machinery fault detection which is part of the predictive maintenance program is still relying on using single axis accelerometer for vibration data acquisition and using a tachometer as a mean of gathering the phase data. To get an absolute phase using a tachometer, a machine needs to be shut-down and re-run again. This conventional practice is seen as time consuming and can be unsuccessful due to lack of skilled and experienced manpower. Conventional machinery fault detection involves expensive and complicated instruments and software and it requires competent personnel to perform machinery fault detection and analyse the output [10].

The primary problem in oil and gas industry and power generation plants around the world is rotor imbalance and misalignment. They cause a lot of problems that lead to other secondary damage [11]. As a result, parts of a machine will suffer, bearings will wear out, foundations will crack, and machines will have a shorter live. Conventionally, maintenance personnel can detect imbalance and misalignment problems from vibration spectra. However, a research found that analysis by depending only to vibration spectrum does not provide the best information for detecting machinery imbalance and misalignment. There are cases where imbalance, misalignment, and looseness are producing the same vibration characteristic, which may lead to false data interpretation and diagnosis [12]. Research works and studies were carried out to explore better method to accurately identify machines part failure. Other alternatives using current signal and Operating Deflection Shape (ODS) analysis were proposed to detect rotor imbalance and misalignment [13]. ODS analysis, which can be performed by using both frequency domain and time domain, is a measurement technique of determining the motion of a structure while it is in operation. The motion of a machine in actual condition at certain frequencies can be obtained from ODS analysis and it helps the personnel to determine the cause of the motion using some digital signal processing technique [14]. Time domain ODS which requires a lot of channels and accelerometers for data acquisition is not practical for predictive maintenance program. On the other hand, a full ODS analysis from frequency domain is more practical to be implemented into machinery fault detection compared to time domain ODS as it reduced the numbers of the accelerometers and number of channels required in the DAQ device. Two accelerometers are adequate to measure the vibration signal with one of the accelerometers remains fixed while the other unit is moving throughout the selected points on the structure [5].

A routine predictive maintenance program requires the machine vibration to be monitored while the machine operation is not interrupted. To date, no research has been done to implement the frequency domain of ODS technique into machinery fault detection and predictive maintenance program. This concept is utilised and was presented by the authors in [14], but the application on real industrial machinery was not covered. The proposed technique is able to gather both vibration and phase data concurrently by using two accelerometers. The usage of two accelerometers is able to provide the phase between two measurement points through relative phase where interruption on the machine operation can be avoided. The phase data is crucial for identifying rotor imbalance and coupling misalignment problem. The proposed technique will eventually enhance current practice of machinery fault detection by reducing time required for performing vibration acquisition and analysis.

2. Background Theories

An ODS depends on the applied forces/loads. Therefore, the forced vibration response of a linear structure for a general system.. For a system which subjected to a harmonic excitation with harmonic force defined by $\{F\} = \{f\}$, a solution form can be derived as $\{x\} = \{X(\omega)\}$, where ω is the excitation frequency, t is the time and $\{X(\omega)\}$ is the location amplitude vector defined as:

$$X(\omega) = \sum_{r=1}^{n} \frac{\{\phi\}_r^T\{F\}\{\phi\}_r}{\omega_r^2 - \omega^2 + 2\sigma_r\omega i} \tag{1}$$

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

In this research, the operating condition on steady-state machinery was not changing during the measurement, therefore, the cross-power spectrum between each roving point DOF and the reference point DOF was adequate. The cross-power spectrum can be written as in:

$$G_{ij}(\omega) = X_i(\omega)X_j^*(\omega) \tag{2}$$

Where X^* is the complex conjugate, i is the measured response and j is the reference response. Only the phase difference between the reference point and roving point is important. Therefore, the Auto-Power Spectrum can be written as in [15]:

$$G_{jj}(\omega) = X_j(\omega)X_j^*(\omega) \tag{3}$$

However, the variation in amplitude part of the auto-power spectrum output is used to measure the absolute amplitude of all points. Combining both the phase differences and amplitudes for all points when linked to the geometry will give the operating deflection. The data can be animated and visualised using DASYLab® software [14].

3. Methodology

In this research, a common accelerometer was used as the reference. The response signal was captured using a tri-axis accelerometer by roving it all around the measurement points. The advantage of using the tri-axis accelerometer is it can cover three measurement acquisitions concurrently, as compared to conventional machinery fault detection practice which relies on single axis accelerometer. Generally, machines consist of a driver and driven machine with two bearings each to support the shaft. Therefore, a 4-point ODS should be enough to simulate the vibration on a machine. This technique requires only four measurement points in providing 12 vibration data. Every measurement points provide the data of vibration amplitude and phase. Both vibration amplitude and phase data are important in displaying machine vibration visualisation.

In the scope of this research, machinery fault detection program is developed in DASYLab®, an icon-based, data acquisition, control, and analysis software package. The program will capture the vibration in acceleration as well as the phase of each measurement point. The relation between this vibration and phase value will gives the visualisation of a 4-point ODS. Same method and procedure were developed by the authors in previous study to prove the concept of the proposed technique [14].

The simplified 4-point ODS technique was then applied on industrial rotating equipment to show the effectiveness of this technique in the implementation in conventional machinery fault detection practice. There were four different types of machine which are suitable in demonstrating the machinery fault such as static imbalance, dynamic imbalance, parallel misalignment and angular misalignment. These machines in petrochemical plant located in east coast of Peninsular Malaysia are vertical centrifugal pump, horizontal centrifugal pump, horizontal centrifugal blower and belt driven centrifugal blower.

Figure 1(a) shows a vertical centrifugal pump. The pump only consists of one bearing which is represented by point 3, while measurement point 4 is located on the pump base. Figure 1(b) shows a horizontal centrifugal pump while Figure 1(c) shows a horizontal centrifugal blower. Both Figure 1(b) and Figure 1(c) represent a common machinery arrangement with four bearings. Figure 2 shows the arrangement of belt driven centrifugal blower. The bearings of the blower are located on top of motor.

Both the motor and the blower shaft are placed inside a cover for safety reason.

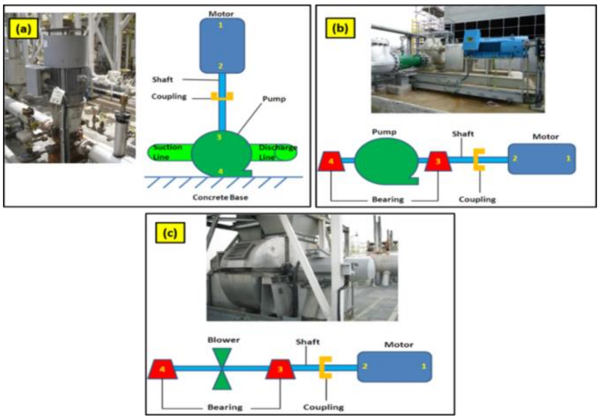

Figure 1. Industrial machinery picture and diagram (a) Vertical centrifugal pump with static imbalance problem (b) Horizontal centrifugal pump with dynamic imbalance problem (c) Horizontal centrifugal blower with parallel misalignment problem

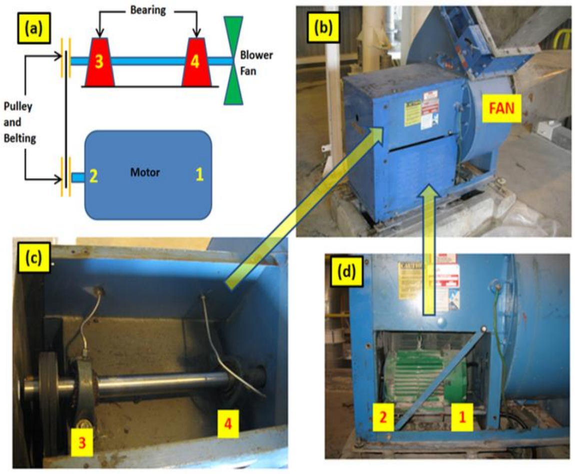

Figure 2. Industrial belt driven centrifugal blower (a) Equipment diagram (b) Equipment photo (c) Blower shaft (d) Motor location

4. Results and Discussion

The testing results on the real industrial machinery using the 4-point ODS technique to identify the machinery fault easily and effectively is deliberated and discussed in this section.

The effectiveness of ODS visualisation was first demonstrated from the industrial vertical centrifugal pump with static imbalance problem. The ODS as shown in Figure 3(a) shows point 1 and point 2 which are both at motor side are moving in relatively higher amplitude and in phase indicates a static imbalance problem. Conventionally, the vibration spectra as in Figure 5(a) were analysed. It shows a harmonic pattern where it may mislead to looseness problem. Further investigation found that the static imbalance problem occurs due to the pipe strain. It is crucial to ensure that both the suction and discharge of the pump are on the same level with the corresponding pipe line to avoid this problem. The proposed simplified 4-point ODS was then tested on an industrial horizontal centrifugal pump which undergoes dynamic imbalance problem. Figure 3(b) shows the ODS of point 3 and point 4 which are both at pump side are moving in relatively higher amplitude and out of phase which indicates the dynamic imbalance problem. Conventionally, the complex vibration spectra as shown in Figure 5(b) were analysed. It could not indicate the imbalance problem with the spectra only. It only shows a frequency component corresponding to the blade passing frequency (BPF). BPF with low vibration amplitude is considered as acceptable. However, due to low discharge pressure, further investigation was conducted. The problem occurred due to severe pump cavitation which causes the pump impeller to worn out. Furthermore, the pump cavitation problem was characterised by the raised noise floor which can be seen in the vibration spectra.

The ODS visualisation of parallel misalignment was then demonstrated from the industrial horizontal centrifugal blower. The ODS is as shown in Figure 4(a) shows that point 2 and point 3, i.e. points across coupling are horizontally out of phase indicating parallel misalignment problem. Conventionally, vibration spectra as shown in Figure 6(a) were obtained where harmonic patterns can be observed in the spectra. Again, this finding may mislead the personnel to diagnose it as looseness problem. The investigation was conducted due to abnormal sound. Although the vibration spectra show relatively lower vibration amplitude, the 4-point ODS is still able to show the motion of parallel misalignment. Further investigation found that the coupling shim was damaged. In addition, the simplified 4-point ODS was tested on a belt driven centrifugal blower with angular misalignment problem. Figure 4(b) shows the ODS that point 2 and point 3, i.e. points across pulley and belting are axially out of phase. Conventionally, vibration with the running speed, 2-time running speed components and multiple harmonic patterns spectra as shown in Figure 6(b) were observed and analysed. The harmonic pattern may mislead to belting looseness. Further investigation found that the vibration remain high after the spare motor was installed. The motor base plate was found flexible and was not properly aligned. Due to uneven level of the motor base plate, the pulley was axially misaligned. By using the 4-point ODS, both parallel and angular misalignment can be detected earlier and easier.

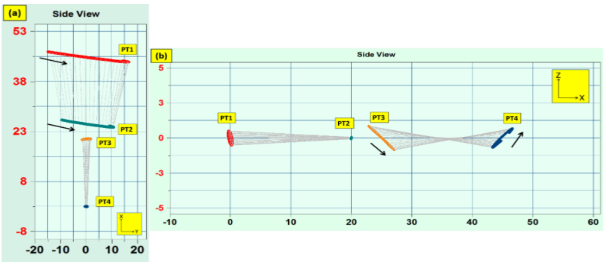

Figure 3. ODS of (a) Static imbalance (b) Dynamic imbalance

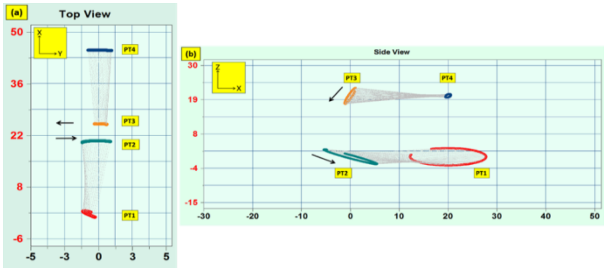

Figure 4. ODS of (a) Parallel misalignment (b) Angular misalignment

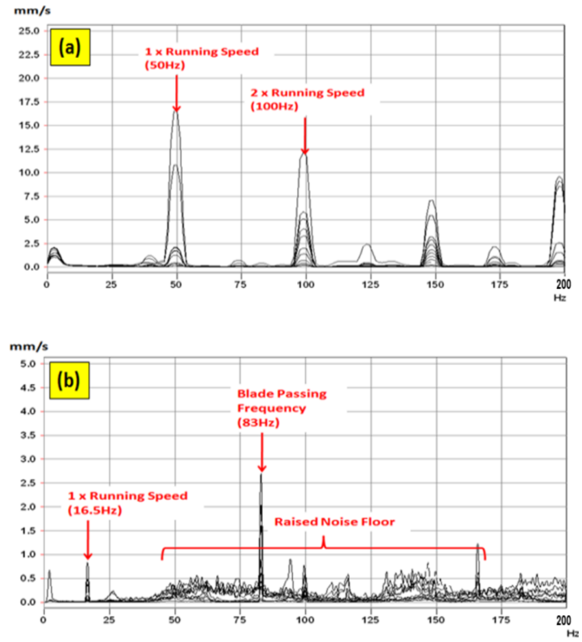

Figure 5. Vibration spectra of (a) Static imbalance (b) Dynamic imbalance

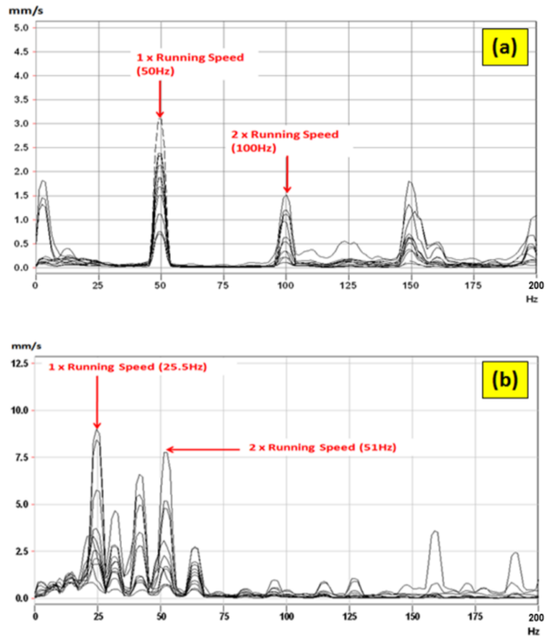

Figure 6. Vibration spectra of (a) Parallel misalignment (b) Angular misalignment

5. Conclusion

Conventionally, machinery failure diagnosis can be performed through transient analysis, steady-state analysis and modal analysis where the machine is totally shut-down. In this research, a simplified machinery fault detection approach using a simplified 4-point ODS shows that a steady-state machine vibration can be analysed without shutting down the machine to acquire the phase data. While other existing analysis method using Nyquist plot and Bode polar are plot only applicable for transient machine vibration which also requires a permanent tachometer or key-phasor as the reference for phase data. Hence, the proposed method shows that imbalance and misalignment can be distinguished easily through machinery motion visualisation without any interruption on the machine operation. Machine motion visualisation is crucial and should be integrated into conventional machinery fault detection practice which relies on vibration spectrum only. From the machine motion visualisation, personnel can visualise the motion of the machine. Therefore, primary machine problem such as imbalance and misalignment can be detected earlier and easier, hence avoiding any secondary failure such as bearing damage, worn impeller, broken rotor bar, and cracked gear teeth in shorter time without analysing every single spectrum. Furthermore, advanced or specialised knowledge is unnecessary for maintenance personnel to apply this technique into machinery fault detection and predictive maintenance program. The integration of this technique will eventually enhance the conventional practice of machinery fault detection by reducing the time required for performing vibration data acquisition and analysis and may possibly reduce downtime cost with early and effective machinery fault detection.

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