Vibration Analysis: Fault Detection and Failure Prediction

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***Abstract* — In industrial applications, the uptime of machines can be enhanced through equipment monitoring. This minimizes the risks of unpredicted failures and consequent plant outages. Since all failure modes can cause an increase in machine vibrations, monitoring this area is the predominant and most widely used method to determine equipment condition, and to predict failures. The objective of this study is to detect faults in rotating equipment with the use of vibration analysis. A motor condition monitoring experiment is set up, and the motor's operational speed is controlled by an AC motor drive. The vibration of the motor is measured and monitored. The measured vibration data is analyzed using spectrum analysis software and a MATLAB program. The overall vibration level is calculated, the vibration severity is compared with the standard severity table and is used to determine the condition of the motor. The specific natural frequency corresponds with which kind of fault or failure mode is identified. This information provide insight on the condition of the machine.**

I. Introduction

Scheduled and fail-then-fix maintenances are commonly used by industries, but both tend to incur much higher costs. Predictive or Condition-Based Maintenance based on known condition is used to predict (and therefore assist in avoiding) unplanned equipment failures. During observation of the vibration modes, a relationship was found between the ranges of natural frequency of vibration and the failure modes. By measuring and analyzing measured vibration data, engineers are able to retrieve valuable information on the status of the equipment, predict machine failure patterns, and plan timely maintenance operations. To progressively extend the time between failures for the monitored equipment, the trend of vibration in frequency domain needs to be observed frequently. The trend of the spectrum will provide information on what type of faults are present within the system, the severity of the fault, and will help determine the remaining lifespan of the machine.

Understanding the concepts behind vibration data allow engineers to detect faults and predict failures caused by equipment defects, or deterioration such as unbalanced rotors, bearing defects, a lack of lubrication, coupling issues, and misaligned axles before they lead to catastrophic failure. To understand how vibration analysis can be used to identify motor faults, one must first understand that all mechanical systems vibrate. This vibration retains a unique signature which, given proper analysis, can tell an operator how the system is responding to its operating conditions. Altering these conditions may reveal different signatures yet, at the same time, patterns emerge suggesting a specific problem within the system. Over time, certain patterns can become more evident suggesting a machine may fail if left uncorrected. Recognizing and categorizing these patters before equipment failure is the objective of fault detection and predictive maintenance, and allows corporations and industries to reduce spending in equipment repair and replacement. This concept correlates to the method of predictive based maintenance.

II. Background Information

Fault detection

The goal of this experiment was to find evidence regarding vibration patterns associated with specific electric motor faults. Specifically, the objective of the experiment was to determine the validity of using vibration analysis to conduct predictive based maintenance. Based on previous research, there are several common motor faults that can be identified using vibration analysis such as imbalance, mechanical looseness, and bearing faults [1]. Each fault condition's severity and type can be assessed based on the amplitudes of the corresponding peaks as well as their respective locations on the frequency spectrum. Additionally, certain types of faults can be determined based on the location were data was recorded on the equipment. In other words, some faults display a higher level of severity when the accelerometer is placed on various locations of the motor. To demonstrate the effects faults have on the motor's corresponding vibration levels, multiple tests were conducted on a three phase inverter duty induction AC motor.

In addition to above mentioned methodologies for fault analysis, some researchers have proposed fault diagnosis methods based on terminal voltage and current measurements. In [2] – [4] the effects of bearing and winding faults on the stator current have been studied. It is shown that using the frequency response analysis one can perform health monitoring or life time prediction on the motor.

Stages of Bearing Failure

Bearing faults are considered the most common case when conducting rotating machinery maintenance; however, unlike more basic faults, bearing faults appear in four stages. During stage one, bearings operate at normal conditions, and can be considered undamaged. At stage two, bearing defect frequencies begin to appear as peaks on the frequency spectrum. According to the article "Rolling Element Bearing Analysis" by Brian Graney and Ken Starry, bearing defect frequencies can be calculated using equations (1) – (4) according to [5]. The amplitudes of these frequencies hint toward the conditions of the bearing, and often increase over time. As the bearing deteriorates, it reaches stage three where multiples of the bearing defect frequencies begin to appear as peaks in the frequency spectrum. It is common practice to replace these bearings after reaching this stage. Finally, at stage four, bearing defect frequencies disappear from the spectrum and replaced by random noise in the low frequencies spectrum [6]. At this stage, the bearing is at the risk of undergoing catastrophic failure which can cost companies thousands in machine repair and/or replacement. By replacing damaged bearings before they fail, industries can drastically reduce the cost of replacing vital machinery therefore outlining the importance of predictive based maintenance on high value equipment.

III. EXPERIMENT SETUP

Three fault conditions were studied in a series of experiments. Each of these experiments were run using a three-phase, inverter-duty, AC electric motor. This motor, was driven using a GS1-10P2 AC drive purchased from Automation Directed and operated at 1725 RPM. Using an accelerometer placed in the vertical axis of the motor, vibration data was recorded using a NI PXI-4498 data acquisition device purchased from National Instruments, and was analyzed using the Sound and Vibration Assistant also purchased from National Instruments.

Unbalance

To study the unbalanced rotor condition, a steel bolt was mounted to one end of a three phase induction motor's flywheel. According to previous research, a motor with an unbalanced rotor will display a large amplitude peak at one times the running speed [1]. Operating at 1725 RPM (30Hz), the motor's vibration data was recorded using a data acquisition device and graphed using an FFT in MATLAB. Figure 1 shows the setup for this experiment.

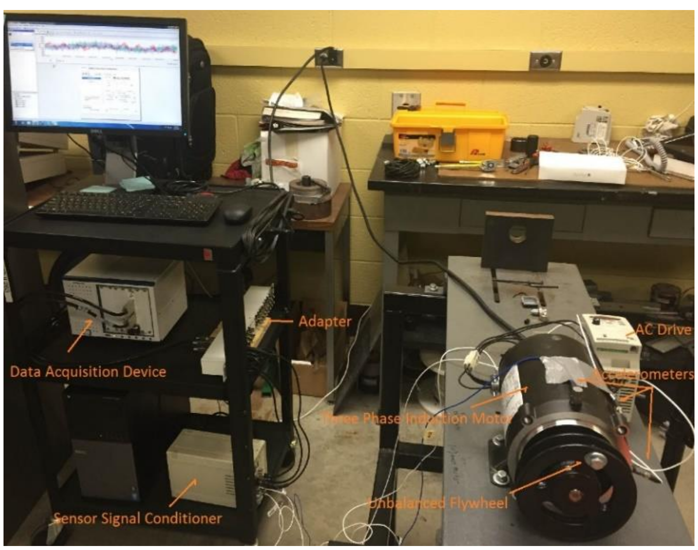

Fig. 1. Experiment setup (Unbalanced condition)

Mechanical looseness

Vibration patterns resulting from mechanical looseness were also studied. By loosening mounting bolts on the three phase electric motor, the body of the motor was allowed to move more freely therefore altering the motor's vibrational patterns. On the frequency spectrum, peaks corresponding with mechanical looseness are considered to appear as many multiples of the motor's running speed. Additionally, these peaks appear on a raised noise floor and display random amplitudes [7]. Similarly to the unbalance experiment, the three phase motor's vibration data was operated at 1725 RPM (30Hz), and recorded using a data acquisition device.

Bearing Fault

In addition to mechanical looseness and unbalance, the patterns relating to bearing failures were also studied. Using a bearing from a three phase induction motor, a defect was created on one of the bearing balls. Figure two shows the generated defect of the rolling element within the motor's bearing.

Fig. 2. Top view of defected bearing

The bearing defect frequencies were also calculated for the motor's 6203-2RS bearing. The values for which can calculated using the following equations:

$$BPFI = \frac{N}{2} * F * (1 + \frac{B}{P} * cos\theta) \tag{1}$$

$$BPFO = \frac{N}{2} * F * (1 - \frac{B}{P} * cos\theta) \tag{2}$$

$$FTF = \frac{F}{2} * (1 - \frac{B}{P} * cos\theta) \tag{3}$$

$$BSF = \frac{P}{2B} * F * [1 - \left(\frac{B}{P} * cos\theta\right)^2] \tag{4}$$

Table 1 shows the calculated values for each bearing fault. Much like the previous tests, the motor was operated at 1725 RPM (30Hz). By doing this, it was predicted the bearing's corresponding frequency spectrum would exhibit traits correlating to one of four stages of bearing failure thus supporting the validity of using vibration analysis to conduct predictive based maintenance. The spectrum plots that have been used in this analysis is based on the algorithm proposed in [8] and [9].

TABLE I. Bearing Fault Frequencies

Bearing Frequency Types	Frequency (Hz)
Shaft Speed Frequency	28.750
Inner race defect frequency (BPFI)	142.223
Outer race defect frequency (BPFO)	87.777
Cage defect frequency (FTF)	10.972
Ball spin frequency (BSF)	57.323
Rolling element defect frequency	14.656

IV. VIBRATION DATA ANALYSIS

Ideal condition

Figure 3 displays the FFT graph for a three phase induction motor operating at 1725 RPM (30 Hz). This data was taken to act as the healthy/ideal condition. To clarify, no fault conditions are placed on the motor. By monitoring the condition of an ideal motor, comparisons can be made between motors under fault conditions and that of an ideal motor.

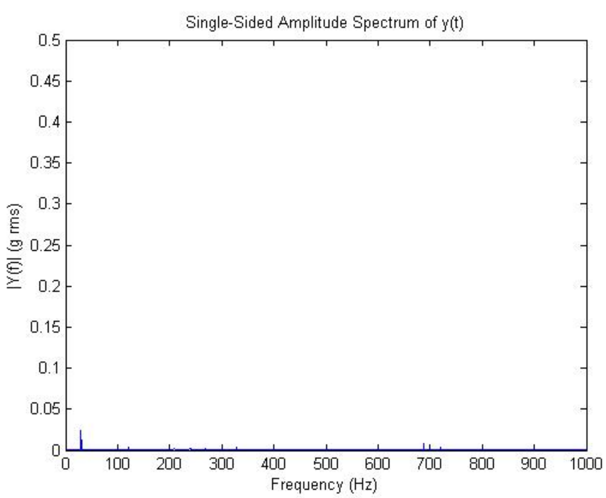

Fig. 3. Motor under normal operating conditions (0-1k Hz)

Unbalance Fault

Based on the data presented in figure 4, several peaks appear to be present. The most notable of which is the peak at 30 Hz. The 30 Hz peak correlates to the running frequency of the motor/s drive axle and has an amplitude of approximately 0.14 g. Compared to the 30 Hz peak seen in figure 3, which displays the motor operating under normal conditions, the 30 Hz peak of figure 4 shows a substantial increase in amplitude. Additionally, the overall noise in figure 4 appears to have changed. These two observations outline can be linked to the motors unbalance condition.

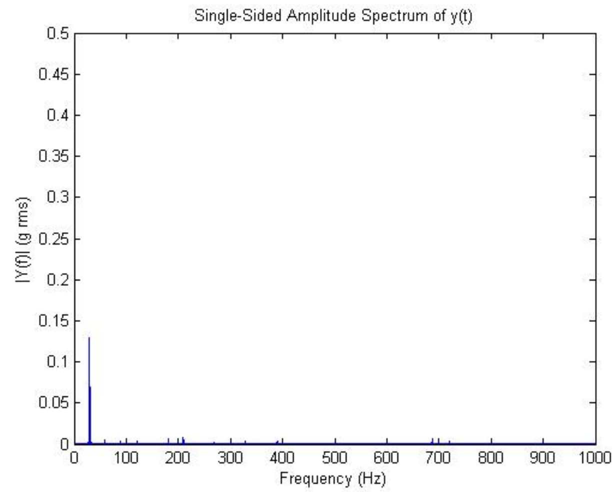

Fig. 4. Unbalance condition

Because the motor's balanced state was the only condition altered during this experiment, it can be stated that the differences between figures 3 and 4 support the presence of unbalance within the system. The unbalance fault condition can be associated with a large increase in the operating speed frequency as well as a raised noise floor. These two conditions agree with the findings of previous research stated in the introduction as well as the experiment setup section of this report.

Mechanical looseness

Figure 5 displays several peaks appearing in the low frequency spectrum. What is most notable of these peaks is that their frequency values are multiples of the running speed. Additionally, these peaks possess a variety of amplitudes each large enough to be considered hazardous to the motor's overall health. If allowed to operate over longer periods of time, it is likely the motor's lifespan will be reduced. Fortunately, mechanical looseness is often easy to address. In this case, simply tightening the bolts on the motor's mounting feet resolves the issue. Figure 3 displays the motor's vibration data with a secure mount. Here, several of the running frequency multiples are no longer present, and the amplitudes of each peak are reduced. These differences show that the presence mechanical looseness condition appears as several multiples of the motor's running frequency as well as a raised noise floor in the spectrum and therefore agree with the conditions stated in [1].

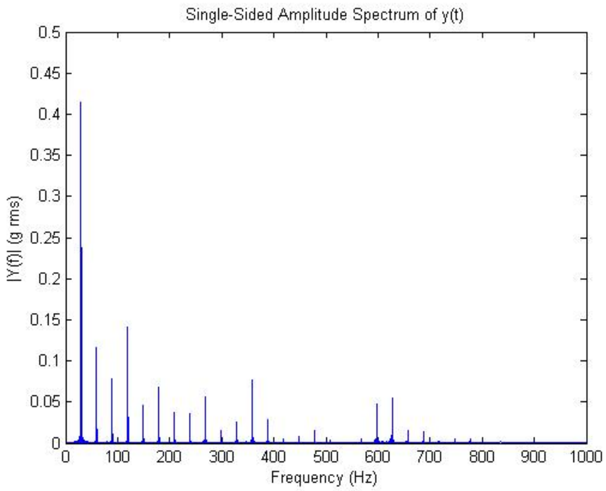

Fig. 5. Mechanical looseness condition

Bearing Fault

Based on the results from Figure 6, it appears the spectrum lacks data relating to the specific bearing fault frequencies stated in table 1; however, because of the severity of the damage placed on the bearing, it is unlikely the motor can be considered to be operating under normal conditions.

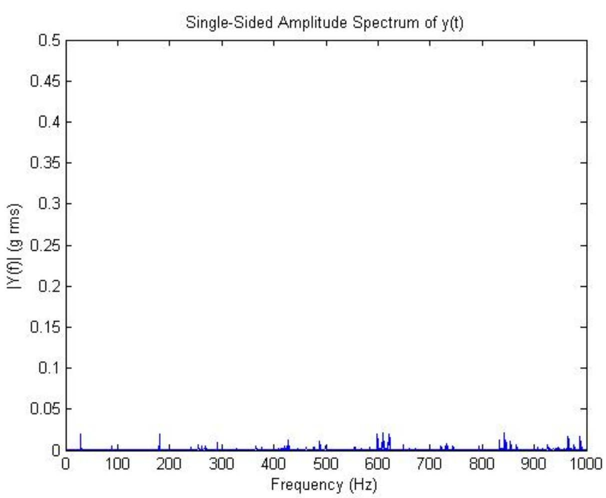

Fig. 6. Damaged bearing (0-1k Hz)

Several notes can be taken from figure 6. For instance, the vibration spectrum displays a raised noise floor as well as a number of low amplitude peaks appearing in the higher frequencies; however, what is interesting to note is that none of these frequencies appear to be whole number multiples of the running speed, or the bearing fault frequencies, nor do these peaks appear to correspond with the unbalance, or mechanical looseness fault conditions, yet it is obvious the motor's vibration data has been affected by the damaged bearing. Comparing these results to the spectrum in figure 3, which shows the motor operating before the bearing was damaged, shows how the motor's vibration data has undergone substantial change and is no longer operating in a healthy state. This suggests two possibilities, either the data collected was inaccurate, or the bearing could have reached stage four of bearing failure.

While it may be easy to assume the data regarding the damaged bearing was faulty, observing the motor's vibration data on a higher frequency suggests stage four of bearing failure. Figure 7 shows the motor's vibration data from zero to ten thousand hertz before the bearing was damaged, while figure 8 shows the same data after the bearing was damaged.

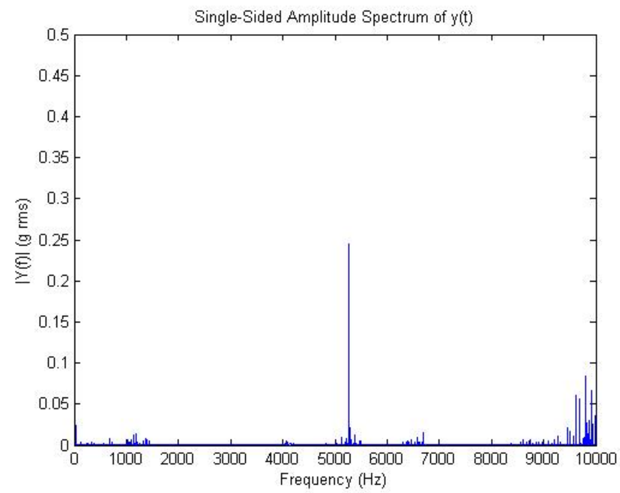

Fig. 7. Undamaged bearing (0-10k Hz)

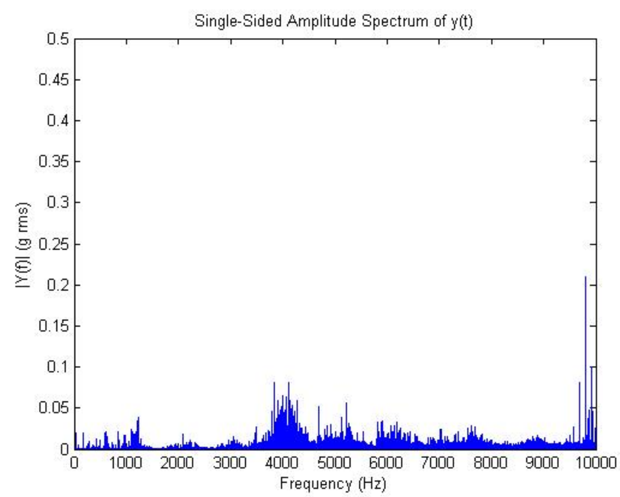

Fig. 8. Damaged Bearing (0-10k Hz)

When comparing figures 7 and 8, one may note the distinctive difference in the overall noise vibration of the motor. Because of this, the bearing could be in stage four of bearing failure. Stage four of bearing failure displays large amounts of noise in higher frequencies; however, at this stage, bearing defect frequencies no longer appear [6]. This information provides an explanation as to why the bearing defect frequencies are not present in the spectrum.

Should this be the case, depending on the importance of the motor, it is important to replace the bearing immediately. It is common practice to prevent more vital machine bearings from reaching stage four of bearing failure, otherwise the bearing is at the risk of experiencing catastrophic failure resulting in damage to vital machine components.

V. CONCLUSION

The results from each of the three tests support the use of vibration analysis in predictive based maintenance. By comparing the vibration data for each fault case to that of a healthy motor, shown in figure 3, the patterns corresponding with each fault condition are outlined. This, therefore, shows how certain faults in rotating mechanical systems can be determined using vibration analysis. Future research will involve the analysis of vibration trends. In other words, this research will involve predicting how, and when, rotating equipment will fail. By developing a time dependent procedure towards assessing motor faults, motors can be operated for the maximum allowed time before being repaired thus reducing overall maintenance costs.

ACKNOWLEDGEMENT

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