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Advancements in Predictive Maintenance: An In-depth Investigation on Vibration Analysis for Detecting Faults and Monitoring the Condition of Vibrating Machinery

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When it comes to maintaining and identifying faults in vibrating machinery, vibration analysis is an essential technique. While fault detection tries to identify and pinpoint a potential issue on the machinery, maintenance examines how effectively the equipment is functioning within its intended boundaries. Through routine or continuous equipment monitoring, machine condition monitoring assesses the state of an operational machine. Compared to time-based or routine maintenance, this method saves money because tasks are only completed when necessary. The benefits of predictive maintenance are numerous. It plans downtime for maintenance and anticipates malfunctions before they happen. A machine's state can be predicted using a variety of methods, such as thermography, current signal analysis, vibration monitoring, etc. According to a number of studies, vibration analysis is the most important predictive maintenance technique because it provides precise information about the state of the machine. Additionally, the precise position of the fault and its potential severity can be determined with the help of the vibration level and frequency. Vibration analysis is based on the idea that any failure in industrial machinery will cause the vibratory signal to either grow or change significantly.

Keywords: Vibration analysis, fault detection, predictive maintenance, machinery reliability, vibration monitoring, predictive techniques, fault diagnosis.

1. Introduction

Vibration refers to the movement of a particle, body, or a group of interconnected bodies that have been shifted from their original balanced state [1,2]. The majority of vibrations in machines and structures are unwanted due to their ability to generate heightened stresses and energy losses, contribute to increased wear and bearing loads, induce tiredness, cause discomfort to passengers in vehicles, and absorb energy from the system. Proper balance of rotating machine elements is essential to avoid any damage caused by vibrations [3]. Vibration is a defining attribute of spinning machines, which is determined by their structural properties and the method of operation. Vibration is a constant occurrence in turbo machines, regardless of whether they are constructed with a linear, cylindrical shaft or a shaft that has a tiny slot, like the ones seen in various mechanical couplings. The experimental findings will demonstrate notable disparities in the machine's behavior, encompassing the orbit, resonance frequencies, as well as the phase and amplitude of mechanical vibrations [4]. The period of the vibration refers to the duration needed to complete a single full cycle of the vibration. If, for instance, the machine completes a single cycle of vibration within a time frame of 1/100th of a second, then the duration of vibration is referred to as 1/100th of a second. While the duration of vibration is a straightforward and significant property, an equally straightforward but more significant criterion is the vibration frequency. While vibration frequency can be quantified and denoted in hertz (Hz), in the context of equipment vibration analysis, it is often measured in cycles per minute, abbreviated as CPM. Conveying the vibration frequency in CPM facilitates the correlation of this attribute with the machine's rotational speed, often denoted in RPM (revolutions per minute). Therefore, when a machine runs at 3000 RPM, it is more significant to be aware that a vibration happens at 3000 CPM (1 times RPM) rather than 50 Hz [3-6]. In practical vibration detection and analysis, it is unnecessary to calculate the frequency of vibration by visually seeing the vibration time waveform, identifying the period of the vibration, and subsequently computing the reciprocal of the period to obtain the frequency. Most contemporary data gathering equipment and vibration analysers offer a straightforward display of the vibration frequencies produced by the machine [7]. Vibration frequency serves as an essential diagnostic tool for identifying and precisely locating certain mechanical or operational issues. The necessity of doing a vibration frequency study relies on the intensity of the machine's shaking. Knowing the frequency or frequencies of vibration present is immaterial if the equipment is working smoothly [8,9]. The vibration amplitude is a measure of the magnitude of vibration, indicating the roughness or smoothness of the machine's vibration. Vibration amplitude can be quantified and represented as vibration displacement, vibration velocity, and vibration acceleration. Vibration displacement is defined as the total distance traveled by the vibrating part between its two extreme limits of movement. This distance is sometimes referred to as the "peak-to-peak displacement." The measurement of vibration displacement is often expressed in either inches or millimeters. Vibration velocity is a quantification of the rate at which a machine or machine part moves during its oscillatory motion. The measurement of vibration velocity is often stated in units of inches per second or millimeters per second. Vibration acceleration is a significant parameter that may be utilized to quantify the amplitude or amount of vibration. Acceleration is defined as the derivative of velocity with respect to time. It is commonly expressed in units of inches per second and millimeters per second. When should we employ vibration displacement, vibration velocity, and vibration acceleration? For speeds below 200 rpm, it is preferable to measure vibration displacement. For speeds between 200 and 10000 rpm, it is preferable to measure vibration velocity. For speeds over 10000 rpm, it is preferable to measure vibration acceleration. An experiment was conducted on a particular configuration to measure its vibration properties [10,11].

2. Literature Review

In recent years, there has been a notable increase in the focus on predictive maintenance as industries aim to improve operating efficiency and minimize downtime. Vibration analysis is a significant approach used in predictive maintenance to discover defects and monitor the condition of vibrating machinery. This literature review intends to examine the latest developments in vibration analysis techniques till the date, with a specific focus on significant research discoveries and approaches described in the following reference:

Authors [12] provided a comprehensive overview of recent advancements in vibration analysis techniques specifically tailored for fault diagnosis in rotating machinery. Wang et al. discussed various signal processing algorithms and machine learning approaches utilized in fault diagnosis, highlighting their effectiveness in improving the accuracy and reliability of condition monitoring systems. Multiple studies emphasize the immediate need for efficient measures to tackle sulfur dioxide emissions and their related effects.

The authors [13] provided a thorough examination of vibration-based methodologies for the diagnosis and prognosis of equipment faults. The study explored several strategies, such as time-frequency analysis, empirical mode decomposition, and artificial intelligence-based techniques like neural networks and support vector machines. The evaluation offered essential perspectives on the strengths and limits of each methodology, assisting researchers and practitioners in choosing suitable techniques for specific applications. In their article, authors [14,15] presented an overview of data-driven predictive maintenance strategies, with a focus on vibration analysis as a key component. The paper discussed the integration of sensor data, machine learning algorithms, and predictive analytics techniques for proactive maintenance planning and decision-making. The insights provided in this review contributed to the development of data-driven maintenance frameworks tailored to the needs of modern industrial systems.

Authors conducted [16,17] a survey of deep learning-based vibration analysis techniques for machinery condition monitoring. The paper explored the application of deep neural networks, convolutional neural networks, and recurrent neural networks in analyzing vibration signals for fault detection and diagnosis. The survey highlighted the potential of deep learning approaches in handling complex vibration data and achieving superior performance compared to traditional methods.

3. Materials and Methods

3.1 Experimental setup description:

This experiment is carried out on a setup as shown in Figure 1. In setup, as shown in sketch Matic Diagram Figure 2, one rotating disk is provided in between two bearings, and that disk is mounted on one shaft, which is rotated by one electric motor.

Figure 1. experimental setup of Rotating Disk Assembly with Dual Bearings and Motor Drive

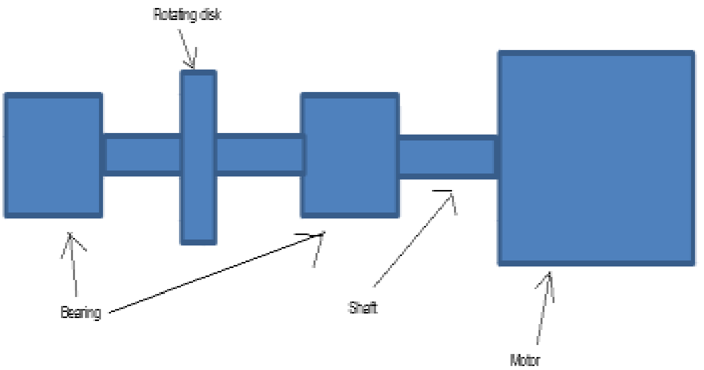

Figure 2. Sketch Matic diagram of experimental setup of Rotating Disk Assembly with Dual Bearings and Motor Drive

3.2 Vibration measuring device

A vibration measurement device was employed to assess acceleration, velocity, and displacement. The operational range of the setup spanned from 200 to 3000 rpm, corresponding to frequencies between 200 and 100,000 Hz. Vibration amplitudes were measured in units of velocity, specifically in millimeters per second (mm/s). The sensor was strategically positioned at the bearing interface between the rotating disk and the motor, as depicted in Figure 1. For further clarity, the configuration of the vibration measuring device is illustrated in Figure 3.

Figure 3. Vibscanner

3.3 Different conditions

The vibration levels of a system were assessed at three distinct positions: horizontal, vertical, and axial. Upon analysis, it was observed that the vibration severity was predominantly noticeable solely in the vertical position. Consequently, all subsequent readings were exclusively conducted in the vertical position.

4. Results and Discussion

The Fast Fourier Transform (FFT) spectra were recorded under various conditions, yielding distinct values of vibration amplitude in velocity. These values are summarized as follows:

4.1 Different positions of the sensor

A sample of the FFT spectrum depicting the vibration in the bearings under normal working conditions at 291 rpm (equivalent to 5 Hz or 5 RPS) is illustrated in Figure 4.

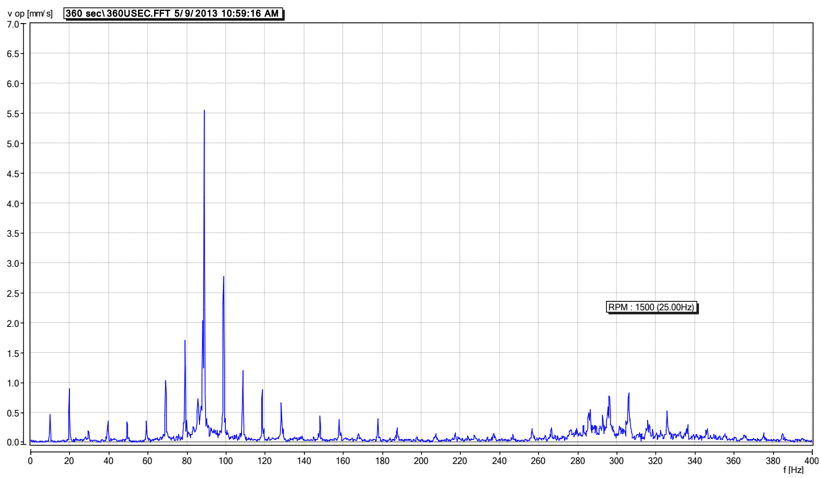

Figure 4: FFT Spectrum for Normal Working Condition at 10 Hz (Vertical Sensor Position)

Table 1: Vibration amplitude in velocity in mm/sec for normal working condition and

different position of sensor.

Frequency (Hz)	Speed (rpm)	Velocity (mm/s)		
		Horizontal	Vertical	Axial
		RMS	RMS	RMS
5	291	2.73	5.56	4.99
6	351	2.84	5.77	5.23
7	410	3.86	6.67	6.26
8	471	7.54	7.06	5.58
9	567	5.15	7.34	6.02
10	595	8.08	10.09	6.64
11	648	7.11	8.42	6.59
12	709	6.74	9.93	7.38

The results were compiled from 24 FFT plots obtained at different rotor speeds and are presented in Table 1. The table indicates that vibration severity is notably higher in the vertical direction compared to the horizontal and axial positions of the sensor. Consequently, all measurements were exclusively taken in the vertical direction. Furthermore, Figure 5 illustrates a continuous increase in vibration amplitude from 5.56 mm/s to 19.93 mm/s with increasing rotor speed, indicating a direct correlation between rotor speed and vibration amplitude

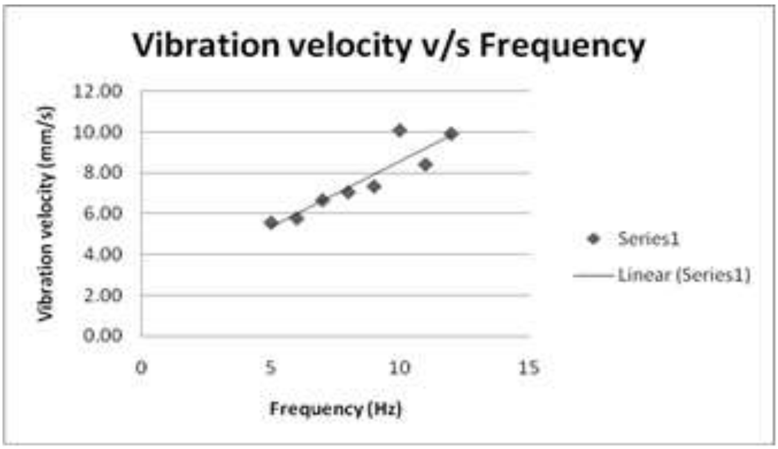

Figure 5. Variation of Vibration Velocity with Speed (Frequency)

4.2 Normal steady working condition

A sample of the FFT spectrum depicting normal steady working conditions after 10 minutes is presented in Figure 6.

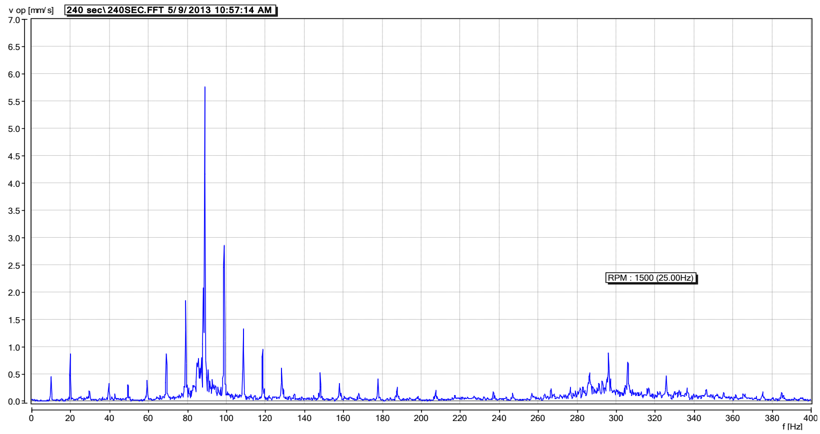

Figure 6. FFT plot for normal steady working condition after 10 min

Table 2: Vibration Amplitude (mm/s) for Normal Working Condition at Various Time Intervals

Time (min)	Velocity (mm/s)
2	6.15
4	6.12
6	6.05
8	5.98
10	5.76
12	5.81
14	5.56
16	5.24

From Table 2, it is evident that the vibration amplitude decreases over time. Specifically, the values decrease from 6.15 mm/s initially to 5.24 mm/s as time progresses, indicating a trend towards stability in the system. This observation is further supported by Figure 7, which visually represents the decreasing trend of vibration amplitude over time, suggesting a transition towards a more steady state.

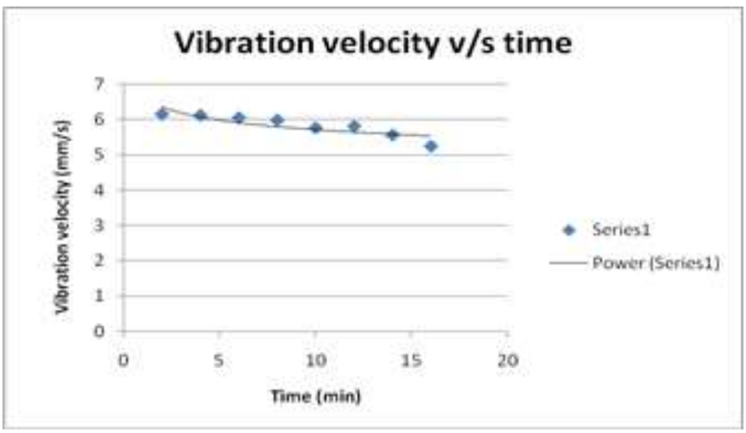

Figure 7. Change in vibration velocity w.r.t. time.

4.3 Effect of unbalanced mass

A sample FFT plot illustrating an unbalanced mass of 17.37 grams at a speed of 599 rpm is depicted in Figure 8.

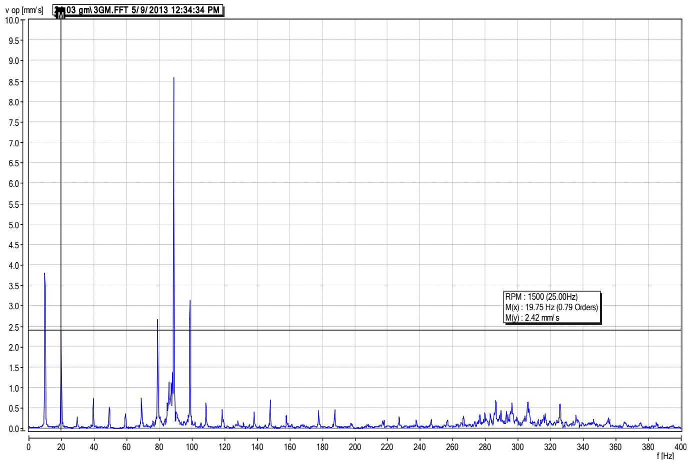

Figure 8. FFT Plot for Unbalanced Mass of 17.37 grams at 599 rpm Speed.

Table 3. Vibration Amplitude (mm/s) for Different Unbalanced Masses

Unbalanced mass (gm)	Velocity (mm/s)
0.00	7.20
8.70	8.04
17.37	8.54
24.03	9.47
33.84	9.92
42.56	12.06
51.22	11.49
59.97	12.95

Table 3 clearly demonstrates a direct correlation between the imbalanced mass and the vibration amplitude, indicating that as the unbalanced mass grows, the vibration amplitude also increases. More precisely, when the mass that is not evenly distributed changes from 0.00 gm to 59.97 gm, the recorded velocities consistently rise from 7.20 mm/s to 12.95 mm/s. This data implies a clear correlation between the degree of imbalance in the system and the ensuing amplitude of vibration.

Within the framework of the results and discussion, this discovery emphasizes the need of counterbalancing spinning machinery to alleviate vibration problems. As the mass that is not evenly distributed grows, the levels of vibration become more intense, which can result in negative consequences such as shorter lifespan of the equipment, more maintenance needs, and decreased operating efficiency. Hence, it is important to employ appropriate balancing procedures to address and reduce imbalance in order to guarantee the utmost efficiency and durability of spinning gear.

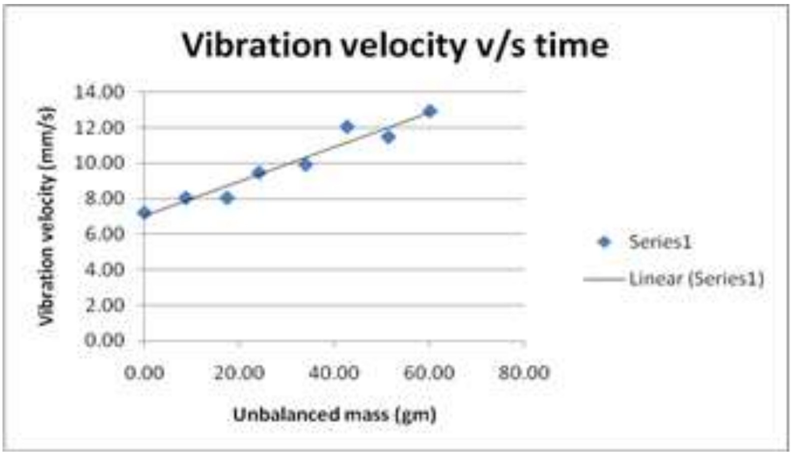

Figure 9. Change in vibration velocity w.r.t. unbalanced mass.

5. Conclusion

Based on the observations from the presented tables and figures:

- Sensor Position Variation: In conclusion, it is evident that the vibration amplitude varies with the position of the sensor in horizontal, vertical, and axial directions. The data highlights the importance of measuring vibration in all directions to determine the direction of maximum vibration severity. Therefore, for any equipment, comprehensive vibration analysis should involve measurements in all directions to accurately assess and address vibration-related issues.

- Speed Variation: Vibration velocity shows a continuous increase with an increase in speed, highlighting the direct correlation between speed and vibration amplitude.

- Time Variation: Vibration readings vary over time, emphasizing the necessity of taking multiple readings to understand the vibration behavior accurately.

- Time Evolution: The decreasing difference in consecutive readings suggests a trend towards reduced and more stable vibration levels over time, attributed initially to high inertia effects.

- Unbalanced Mass Variation: As the unbalanced mass increases while maintaining constant frequency and speed, vibration amplitude continuously increases, indicating a direct relationship between unbalance magnitude and vibration severity. where the frequency of the power supply is held constant at 10 Hz and the speed of the setup remains steady at 599 rpm, the data demonstrates that increasing the unbalanced mass from 0 gm to 60 gm leads to a continuous increase in vibration amplitude. Despite maintaining constant operating conditions, the observed trend underscores the significant impact of unbalanced mass on vibration severity. This highlights the critical importance of balancing equipment to minimize vibration-related issues and ensure operational stability.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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