Experimental Investigation of Fault Simulation in Rotating Machinery

Priyanka Patil[a], Dinesh Chawde[a], Yash Mhatre[a]

[a]*Department of Mechanical Engineering, K J Somaiya College of Engineering, Somaiya Vidyavihar University, Mumbai, India*

Abstract: Fault diagnosis is extremely important because it helps to identify and fix problems in machines or systems quickly. This paper investigates an experimental fault diagnosis in rotating machinery using the Tiera Machinery Fault Simulator. Four common faults in rotating machinery i.e. rotating unbalance, misalignment, faulty bearings, and bent shafts are studied here. Our approach involves analyzing vibration signals in both the time and frequency domains. To simulate real-world conditions, the experimental setup and procedures were meticulously designed. The time domain data obtained from the fault simulator is processed in MATLAB® to obtain the frequency domain spectrum using the Fast Fourier Transform (FFT). To capture fundamental frequencies from the frequency domain data, the initial dominant frequency peak readings are recorded. Significant shifts in the amplitude vs. time/frequency domain data are observed for various faults as compared to an intact system without fault. The presented findings from various fault simulation studies can be very useful for predictive maintenance, safety issues, reliability, and vibration monitoring of rotating machinery.

Keywords: Fault diagnosis, Machinery fault simulator, Vibration monitoring

1. INTRODUCTION

Vibration monitoring is becoming more important in helping with maintenance by predicting and preventing problems and making plants run more efficiently. It's used to detect early signs of machinery issues and diagnose faults (White, 1984). For instance, researchers like Renwick and Babson show how analyzing vibrations can help plan maintenance schedules and manage spare parts better to reduce downtime (Renwick and Babson, 1985). Rahman and Uddin focused on using vibration signals to detect faults in induction motors(Rahman and Uddin, 2017). Song et. al. have carried out the automatic diagnosis of low-speed bearings by using vibration analysis (Song, Wang and Chen, 2018).

Other researchers, like Khot and Khaire, experimentally investigate how misalignment affects rotor bearing systems (Khot, Rodrigues and Khaire, 2015). Machine learning models, as proposed by Khaire and Phalle, are used to identify different types of bearing faults at various speeds (Khaire and Phalle, 2023). Shah and Guha use statistical features to detect faulty bearings from vibration data, while Ratnam et al. explore using acoustic emission and machine learning for fault detection. Ratnam et al. used a data-driven approach using acoustic emission instead of vibration analysis. They have also used machine learning techniques, such as Artificial Neural Network (ANN) and Support Vector Machines (SVM), to detect fault present at outer race and its severity. The defect intensity can be identified by using machine learning model and it was noticed that ANN gives a better size prediction as compared to SVM with an error of 6.57% (Khaire and Phalle, 2023).

In theoretical studies, many authors use simulation-driven vibration to identify faults in ball bearings, focusing on how signals change when there's a defect (Kankar, Sharma and Harsha, 2011; Saruhan *et al.*, 2014; Haj Mohamad and Nataraj, 2021). When there's a problem in a machine part, like a bearing, the vibration pattern changes. Researchers found that this change depends on how big the problem is. They noticed that when a bearing is faulty, the vibration peaks at specific frequencies and has extra signals around those peaks. But in a healthy bearing, the vibration peak appears at a different frequency. Detecting these issues early is crucial to make machines last longer and cost less to maintain. That's why they want to study how misalignment affects machines using both experiments and simulations (Al-Khazali and Askari, 2012; Al-Khazraji, Jweeg and Bakhy, 2024). Phadatare and Pratiher made progress in figuring out how vibrations change in a fast-spinning rotor with unbalanced weight (Phadatare and Pratiher, 2016). Yadav and colleagues

studied how a rotor behaves when it's unbalanced and has some extra space inside the roller bearing (Yadav, Upadhyay and Harsha, 2013). Sadda and Punekar looked at the vibration data from an induction motor with a bent shaft and found that the vibration gets worse because of the faulty shaft (Sadda and Punekar, 2020). Tsai and Wang figured out the size and location of the crack in the shaft by comparing the basic vibration patterns of the rotating shaft with and without the crack (Engineering, 1996). The fault diagnosis related studies addressing common faults in rotating machinery using signal processing technique are widely reported in the literature (Bendjama, Bouhouche and Boucherit, 2012; Cong *et al.*, 2013; Lei *et al.*, 2013). Few more relevant review articles based on the fault diagnosis can be referred from ('Edwards1998 - Diagnosis.pdf', no date; Saufi *et al.*, 2019). Overall, these studies emphasize the importance of detecting various faults early to prolong machine life and reduce costs.

In this paper, we investigated four distinct issues using the Tiera Machinery Fault Simulator to observe their impact on vibrations over time and across various frequencies. The problems we examined were rotating unbalance, misalignment, faulty bearings, and a bent shaft. We analyzed the changes in vibrations in the time domain and subsequently used MATLAB® to transform this data into the frequency domain. This process enabled us to identify the primary frequencies by detecting the most prominent peaks in the data. Our main aim is to investigate the effect of various faults in rotating machinery on the vibration response by using TIERA machinery fault simulator. The experimental results obtained in the form of frequency and time domain responses are beneficial for early detection of faults, predictive maintenance, safety, reliability, and integrity of rotating machineries.

The structure of this paper is organized into three additional sections. Section 2 provides a detailed explanation of the experimental setup and procedures. This is followed by the Results and Discussion in Section 3. Finally, Section 4 elaborates on the conclusion and future scope of this work.

2. EXPERIMENTAL SETUP AND PROCEDURE

The experimental set-up for simulating various faults in rotating machinery is shown in Fig. 1. Fig 1(a) shows the entire set-up integrated with the computer interface, whereas Fig. 1(b) shows the rotating

machinery snaps indicating shaft and disc assembly views which are subjected to motor induced vibrations. It is the FFT-based fault simulator in which the various components are arranged as indicated in the schematic diagram Fig. 2. It consists of a rotating disc assembly in which two circular discs are mounted on a rotating shaft. A shaft is connected to a motor on one end, while its other end is free. The entire assembly is mounted on a sturdy frame with adjustable mounts, ensuring stability during operation. Two rotating discs are assembled on the shaft by keeping equal spacing from mounts on both sides. Data acquisition sensors are placed on one of the mounts as shown in the schematic diagram which sense the vibration signals and simulate the frequency and time domain responses. These responses are captured from the integrated computer system.

(a)

(b)

Fig. 1 Experimental set-up for fault diagnosis simulator (a) Entire integrated set-up showing interface with computer system (b) Rotating shaft and disc assembly snap.

The proposed experimental set-up of fault diagnosis gives the provision to simulate four different types of faults. The commonly occurring faults considered in this study include unbalance, bearing fault, misalignment, and bent shaft. The frequency and time domain responses of a healthy rotating system are compared with faulty systems and this comparison helps to understand the shifts in the frequency and time domain spectrums of a vibrating system. To analyze the influence of a single fault at a time, each of the above-mentioned faults is induced in the

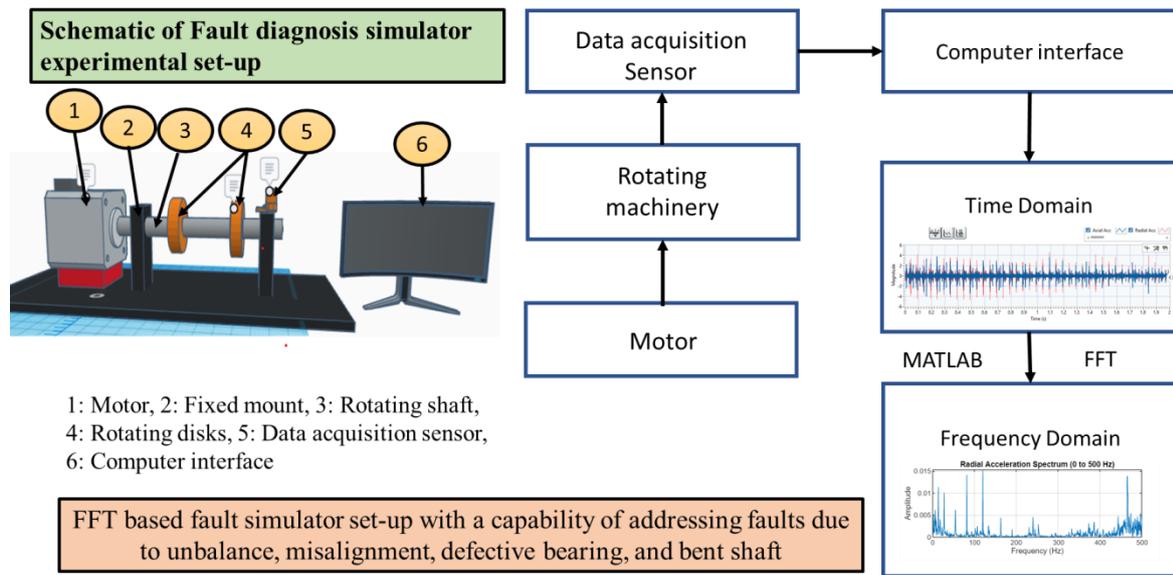vibrating system and the frequency and time domain outputs are captured for an unhealthy system.

Fig. 2 Schematic layout of experimental fault simulator set-up for diagnosis of faults in rotating machinery.

To simulate a fault due to unbalance, multiple holes are drilled on the disc in a circular array in which tiny masses can be mounted to achieve the effect due to out-of-plane and in-plane unbalance. The attachment of masses in particular holes gives the provision to achieve out-of-plane or in-plane unbalanced conditions. How the attachment of a tiny mass is carried out while simulating fault due to unbalance in this study is shown in Fig. 3(a). As the main function of ball bearings in the rotating shaft assembly is to minimize the friction of the rotating shaft in the housing, any fault in the bearings may lead to unstable vibrations. In this paper, the fault in ball bearings is simulated by taking a defective bearing with an initial pre-crack present in the inner race. The bearing with an initial crack in the outer race is also considered in the simulation. The cracked bearing utilized in the current experimentation to simulate fault due to inner and outer race cracks is shown in Fig. 3(b). After these commonly observed faults, in the next simulation, a fault due to misalignment of the shaft is considered in this work for which the frequency response is captured with solid and flexible couplings. In this study, to simulate misalignment, one of the mounts is slightly uplifted by very thin shims, which create eccentricity of the shafts in the assembly. To get clarity on the incorporation of misalignment fault in this study, Fig. 4(a) can be referred. Finally, the fault due to the bending of a shaft is simulated by replacing the straight shaft in the rotating assembly with a slightly bent shaft, and the influenced vibrations are sensed and captured in the integrated computer system. The schematic representation of a bent shaft is shown in Fig. 4(b).

In all the types of simulations, the motor speed is adjusted with the help of variable frequency drive. The frequency and time domain spectrums are obtained from simulations of all four faults mentioned above. The current fault simulator is integrated with the FFT-based system. The frequency and time domain data of a faulty system considering one fault at a time are compared with intact system data to analyze the influence due to each fault. For a comparison of intact and faulty system data, the time and frequency domain responses obtained for a particular motor speed are taken into account.
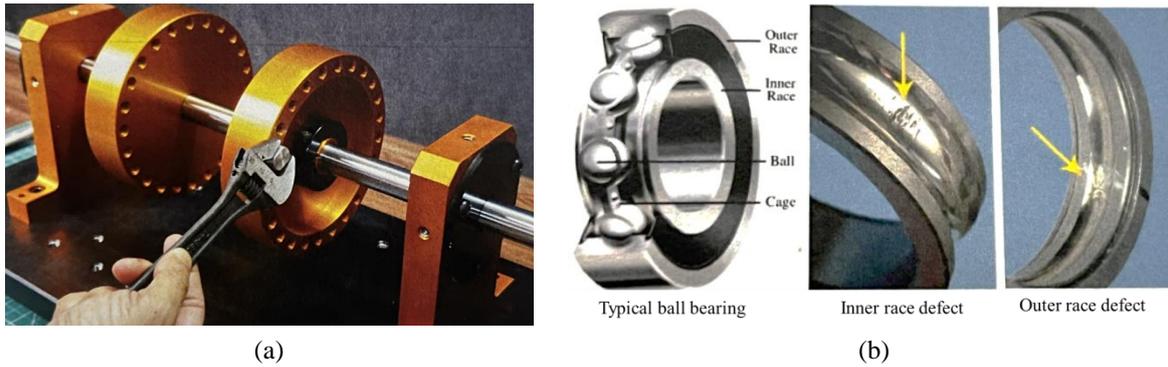
| (a) | (b) |

Fig. 3 Various faults in the rotating shaft-disc assembly (a) unbalance (b) faulty ball bearing with pre-crack at inner race.

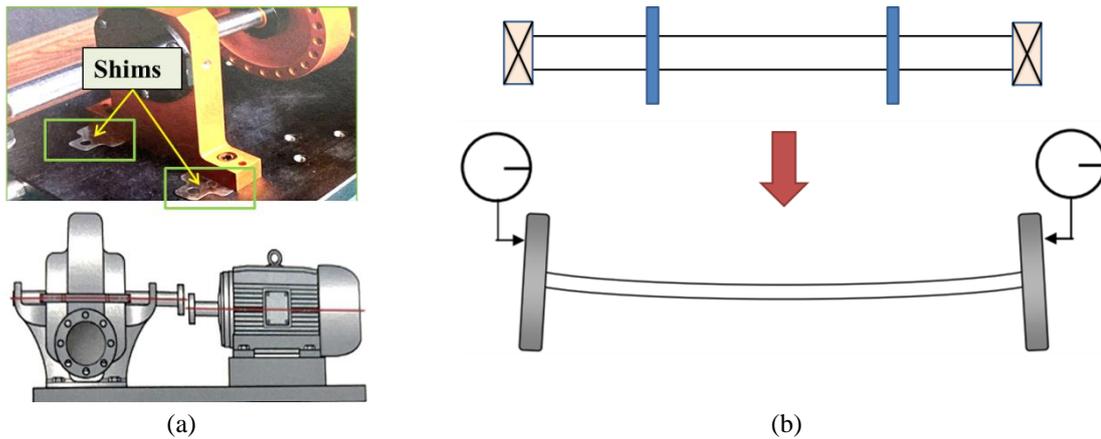| (a) | (b) |

Fig. 4 Various faults in the rotating shaft-disc assembly (a) misalignment (b) bent shaft.

During simulation, the desired fault type is selected, and the motor is started to initiate the vibrations in the shaft. Data acquisition sensors collect and process the data in the form of amplitude of vibration vs. time plot (time domain data). This real-time data is processed using Fast Fourier Transform (FFT) techniques in MATLAB® to obtain frequency plots, which are crucial for identifying and understanding the specific characteristics of each fault.

3. RESULTS AND DISCUSSIONS

The fault diagnosis simulation results of rotating machinery are obtained by using the FFT technique. The time domain data which captures the amplitude vs. time spectrum of intact vibrating machinery is shown in Fig. 5. The influence of an increase in speed on the time domain spectrum is showcased in Fig. 5 for 800 RPM, 1200 RPM, and 1600 RPM. The amplitude vs. time spectrums indicate the radial as well as axial component of accelerations. The radial component is marked in blue color while the axial component is in red as indicated in Fig. 5. It is observed that the amplitude of vibration due to axial and radial acceleration components increases with the increase in the speed. This is due to the fact that,

with an increase in speed the centrifugal forces are increased in the vibrating systems which leads to an increase in the amplitude of vibration. More than a 50% increment in the higher peak of the amplitude is reported when the motor speed is doubled (from 800 RPM to 1600 RPM).
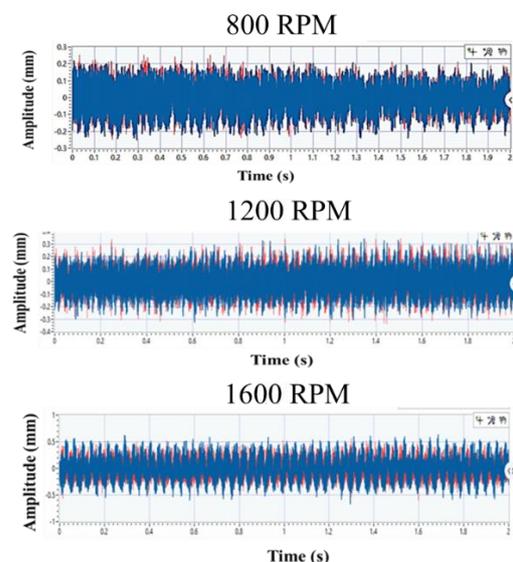

Fig. 5 Time domain spectrums of a healthy rotating vibrating machinery for different speed ranges.

After this, the time domain response is captured at various speeds by setting up faults one by one in the Tiera machinery fault simulator. At first, the fault due to unbalance is simulated by mounting three tiny weights of 8 grams to the discs in one plane. Due to these added masses in the unbalanced positions, the affected time domain spectrum of a vibrating machinery is recorded as shown in Fig. 6(a). This time domain data is processed further in MATLAB® coding using FFT analyzer and the amplitude vs. frequency plot is generated as shown in Fig. 6(b) for intact and unbalanced conditions.
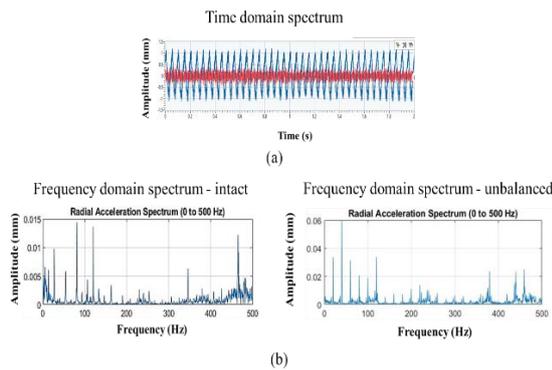

Fig. 6 Results of fault simulation due to multi-mass unbalance (a) Time domain data for unbalanced condition (b) frequency domain data for intact system and unbalanced system.

A comparison of a time domain spectrum for an unbalanced state shown in Fig. 6(a) and that of an intact system shown in Fig. 5 for a consistent speed of 1200 RPM is carried out. It is observed that there is a dominant increment in the amplitude of vibration due to an unbalance fault. A higher peak of amplitude for the unbalanced state is observed at 1.1 mm whereas the same peak for the intact system without fault is at 0.32 mm. The frequency plots for 0 to 500 Hz frequency range are obtained by processing time domain data in MATLAB®. The amplitude vs. frequency plots for the intact system and unbalanced system are shown in Fig. 6(b). The close observation of the first peaks of these frequency domain data shows that, for an intact system the first peak is observed at 26.5 Hz with an amplitude of vibration of 0.010 mm. However, the simulation results of the unbalanced system indicate a first peak at 19.70 Hz with an amplitude of vibration of 0.033 mm. These observations from experimental data indicate a notable shift in the first natural frequency peak of rotating machinery due to the influence of unbalanced masses.
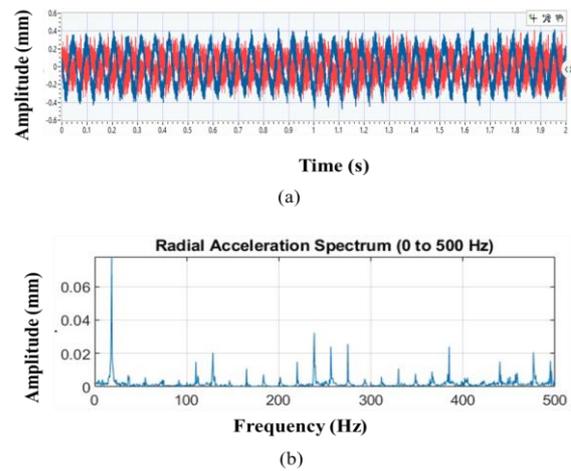

Fig. 7 Results of fault simulation due to misalignment of the shaft (a) Time domain data (b) frequency domain data.

After simulating a fault due to unbalance, in the next step, the fault due to misalignment of the shaft is considered. In this simulation, the flexible coupling is used to support the shaft. The fault due to misalignment is incorporated in the set-up by uplifting one of the fixed mounts by inserting thin shims below it as shown in Fig. 4(a). The time domain plot for misaligned vibrating shaft set-up is shown in Fig. 7(a) and the frequency domain plot for a range of 0 to 500 Hz frequency processed from MATLAB® is shown in Fig. 7(b). It is observed from Fig. 7(a) that the maximum amplitude of vibration is 0.4 mm for 1200 RPM speed. As compared to the time domain response of the intact vibrating system, the amplitude of vibration is observed to be increased by a notable amount of around 20% due to the influence of a misalignment fault. The frequency domain data gives the first peak at 19.77 Hz and an amplitude of 0.078 mm for a faulty simulation with misalignment. This indicates an almost 25.39% shift in the fundamental frequency peak value with a notable increment in the amplitude of vibration.

In the next step, the fault due to defective bearing is simulated. The presence of cracks in the inner race and outer race of bearings are taken into account respectively and the time domain response plots are shown in Fig. 8(a). The amplitude vs. frequency plot is indicated in Fig. 8(b). The plots taken in Fig. 8(a) and 8(b) are for 1200 RPM speed. These time domain and frequency domain plots are compared with the plots of the intact system with 1200 RPM speed. It is observed that the initial crack in the inner race of a ball bearing shoots the amplitude of vibration drastically as compared to that for the intact system

captured in Fig. 5 (refer to 1200 RPM plot). The time domain spectrum for a defective bearing with outer race fault is observed to be comparatively less sensitive as fewer increments in the amplitude of vibration are reported.
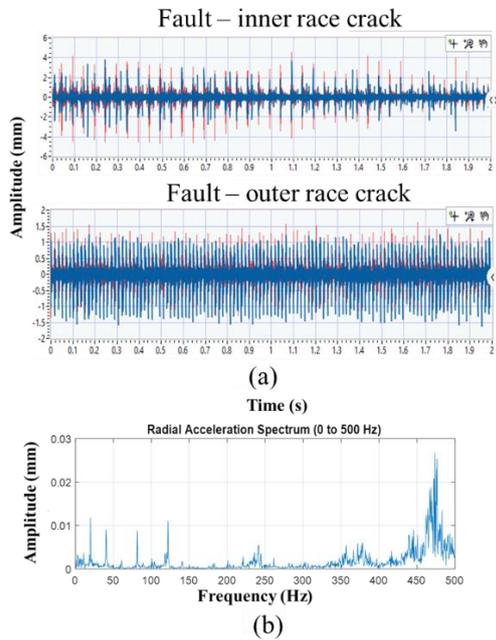

(a)

(b)

Fig. 8 Results of fault simulation due to defective bearing (a) Time domain data - for defective bearing with inner and outer race cracks (b) frequency domain data- with inner race crack.

In the last simulation, a fault due to a bent shaft is considered. A time domain and frequency domain plots obtained from the computer interface and MATLAB® are sequentially presented in Fig. 9(a) and 9(b) respectively. Almost a 23.5% reduction in the first natural frequency is observed due to the influence of the bent shaft.
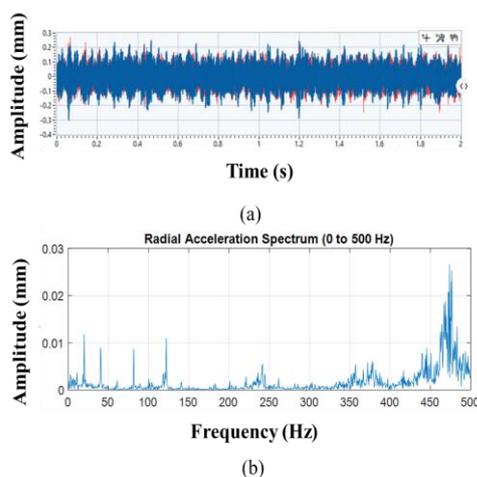

(a)

(b)

Fig. 9 Results of fault simulation due to bent shaft (a) Time domain data (b) frequency domain data.

It is collectively observed from the results presented for the above-mentioned cases that, a defective bearing fault at the inner race of the bearing should be monitored on high priority as notable shifts in the amplitude of vibration and frequency peaks are reported.

4. CONCLUSION

This paper presents an experimental investigation into various common faults in rotating machinery, with the results simulated and presented in both time and frequency domain spectrums. The study begins by discussing the results for an intact rotating vibrating system, followed by the results for faulty systems, each considering one fault at a time. The experimentation focuses on faults caused by unbalance, misalignment, defective bearings, and bent shafts. Notably, a fault due to an initial crack in the inner race of a ball bearing is identified as the most sensitive, causing significant shifts in natural frequency peaks and notable increase in vibration amplitude compared to healthy systems. The fault due to unbalance, caused by multiple masses attached in a single plane, also results in a notable shift in the fundamental frequency peak due to additional centrifugal forces from the rotating masses. Detailed observations of the initial natural frequency peaks in faulty systems reveal significant changes in peak values compared to a healthy system. These shifts in frequency peaks correspond to changes in vibration modes due to the presence of faults. Therefore, the observed fluctuations in frequency and amplitude shifts, when introducing a single fault at a time, highlight the importance of this experimental study in aiding early fault detection using frequency and time domain data. Future work will focus on refining diagnostic techniques and exploring additional fault types to enhance predictive maintenance strategies

Declaration of conflict of interests
The authors declared no potential conflicts of interest with respect to the work, authorship, and/or publication of this article.

REFERENCES

[1] Al-Khazali, H.A.H. and Askari, M.R. (2012) 'The Experimental Analysis of Vibration Monitoring in System Rotor Dynamic with Validate Results Using Simulation Data', ISRN Mechanical Engineering, 2012, pp. 1–17. Available at: https://doi.org/10.5402/2012/981010.

[2] Al-Khazraji, M.S., Jweeg, M.J. and Bakhy, S.H. (2024) 'Free vibration analysis of a laminated honeycomb sandwich panel: a suggested analytical solution and a numerical validation', Journal of Engineering, Design and Technology, 22(2), pp. 316–343. Available at: https://doi.org/10.1108/JEDT-10-2021-0536.

[3] Bendjama, H., Bouhouche, S. and Boucherit, M.S. (2012) 'Application of Wavelet Transform for Fault Diagnosis in Rotating Machinery', International Journal of Machine Learning and Computing, 2(1), pp. 82–87. Available at: https://doi.org/10.7763/ijmlc.2012.v2.93.

[4] Cong, F. et al. (2013) 'Vibration model of rolling element bearings in a rotor-bearing system for fault diagnosis', Journal of Sound and Vibration, 332(8), pp. 607-620, . Available at: https://doi.org/10.1016/j.jsv.2012.11.029.

[5] Edwards1998 - Diagnosis.pdf 'Fault diagnosis in rotating machinery', The shock and vibration digest, vol 30, January 1998, Sage publications.

[6] T C Tsai and Y Z Wang, 'Vibration analysis and diagnosis of a cracked shaft' Journal of Sound and Vibration, 1996, 192(3), pp.607-620, Available at : https://doi.org/10.1006/jsvi.1996.0209

[7] Haj Mohamad, T. and Nataraj, C. (2021) 'Fault identification and severity analysis of rolling element bearings using phase space topology', JVC/Journal of Vibration and Control, 27(3–4), pp. 295–310. Available at: https://doi.org/10.1177/1077546320926293.

[8] Kankar, P.K., Sharma, S.C. and Harsha, S.P. (2011) 'Rolling element bearing fault diagnosis using autocorrelation and continuous wavelet transform', JVC/Journal of Vibration and Control, 17(14), pp. 2081–2094. Available at: https://doi.org/10.1177/1077546310395970.

[9] Khaire, P. and Phalle, V. (2023) 'A smart fault identification system for ball bearing using simulation-driven vibration analysis', Archive of Mechanical Engineering, 70(2), pp. 247–270. Available at: https://doi.org/10.24425/ame.2023.145583.

[10] Khot, S.M., Rodrigues, F.C. and Khaire, P. (2015) 'Simulation and Experimental Study for Diagnosis of Misalignment Effect in Rotating System', Columbia International Publishing Journal of Vibration Analysis, 3(2), pp. 165–173. Available at: https://doi.org/10.7726/jvamc.2015.1009.

[11] Lei, Y. et al. (2013) 'A review on empirical mode decomposition in fault diagnosis of rotating machinery', Mechanical Systems and Signal Processing, 35(1–2), pp. 108–126. Available at: https://doi.org/10.1016/j.ymssp.2012.09.015.

[12] Phadatare, H.P. and Pratiher, B. (2016) 'Nonlinear Frequencies and Unbalanced Response Analysis of High Speed Rotor-Bearing Systems', Procedia Engineering, 144, pp. 801–809. Available at: https://doi.org/10.1016/j.proeng.2016.05.089.

[13] Rahman, M. and Uddin, M.N. (2017) 'Online Unbalanced Rotor Fault Detection of an IM Drive Based on Both Time and Frequency', IEEE Transactions on Industry Applications, 53(4), pp. 4087–4096. Available at: https://doi.org/10.1109/TIA.2017.2691736.

[14] Renwick, J.T. and Babson, P.E. (1985) 'Vibration Analysis-A Proven Technique Maintenance Tool Predictive', I(2).

[15] Sadda, A. and Punekar, G.S. (2020) 'Vibration Data and Analysis of A Large rating Induction Motor with Bent Shaft : Some Aspects', pp. 1–5. Available at: https://doi.org/10.1109/PICC51425.2020.9362445.

[16] Saruhan, H. et al. (2014) 'Vibration analysis of rolling element bearings defects', Journal of Applied Research and Technology, 12(3), pp. 384–395. Available at: https://doi.org/10.1016/S1665-6423(14)71620-7.

[17] Saufi, S.R. et al. (2019) 'Low-Speed Bearing Fault Diagnosis Based on ArSSAE Model Using Acoustic Emission and Vibration Signals', IEEE Access, 7(November 2021), pp. 46885–46897. Available at: https://doi.org/10.1109/ACCESS.2019.2909756.

[18] Song, L., Wang, H. and Chen, P. (2018) 'Vibration-Based Intelligent Fault Diagnosis for Roller Bearings in Low-Speed Rotating Machinery', IEEE Transactions on Instrumentation and Measurement, 67(8), pp. 1887–1899. Available at: https://doi.org/10.1109/TIM.2018.2806984.

[19] White, M.F. (1984) 'Simulation and Analysis Signals of Machinery', Journal of Sound and Vibration, 93(1), pp. 95–116.

[20] Yadav, H.K., Upadhyay, S.H. and Harsha, S.P. (2013) 'Study of effect of unbalanced forces for high speed rotor', Procedia Engineering, 64, pp. 593–602. Available at: https://doi.org/10.1016/j.proeng.2013.09.134.