LOW-COST CONDITION MONITORING FOR UNBALANCED MOTOR SYSTEMS USING TUNED DYNAMIC VIBRATION ABSORBER

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by

MOHD AFFAN BIN MOHD ROSLI

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LIST OF SYMBOLS

g	Gravitational acceleration
v	Instantaneous linear velocity
EI	Flexural rigidity of the beam
A	Cross-sectional area
e	Eccentric mass offset
m_a	Mass of the TDVA
k_a	Stiffness of the TDVA
L	Length of the beam
ω_a	Natural frequency of TDVA
$F(t)$	Periodic forcing function
t	Time
E	Modulus of elasticity
f_n	Excitation frequency
I	Moment of inertia

LIST OF ABBREVIATIONS

DVA	Dynamic Vibration Absober
TDVA	Tuned Dynamic Vibration Absober
CBM	Condition Based Monitoring
RPM	Revolution Per Minute
MEMS	Micro-Electro-Mechanical Systems
SDM	Structural Dynamic Modification
EMA	Experimental Modal Analysis
FRF	Frequency Response Function
IoT	Internet of Thing
Wi-Fi	Wireless Fidelity
LoRaWAN	Wide Area Network
IMU	Inertial Measurement Unit
USB	Universal Serial Bus
I2C	Inter-Integrated Circuit
ASCII	American Standard Code for Information Interchange
HDMI	High Definition Multimedia Interface
GPIO	General-Purpose Input/Output
RAM	Random Access Memory
SDOF	Single-Degree-Of-Freedom
HVAC	Heating, Ventilating and Air Conditioning
AC	Air Conditioning
HAV	Hand-Arm Vibration
IMS	Intelligent Manufacturing System

FFT	Fast Fourier Transform
DLPF	Digital Low Pass Filter
ODS	Operational Deflection Shapes
LAN	Local Area Network
RMS	Root Mean Square
ISO	International Organization for Standardization

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PEMANTAUAN KEADAAN BERKOS RENDAH UNTUK SISTEM MOTOR TIDAK SEIMBANG MENGGUNAKAN PENYERAP GETARAN DINAMIK TERTALA

ABSTRAK

Motor-alur tak seimbang merujuk kepada keadaan sistem berputar di mana terdapat pengagihan jisim yang tidak sekata mengakibatkan getaran atau masalah ketidakseimbangan yang ketara. Pengurusan motor-alur tidak seimbang yang kurang baik boleh menyebabkan pelbagai isu seperti peningkatan getaran, pengurangan kecekapan dan kerosakan yang boleh berlaku samada pada motor itu sendiri mahupun pada bahagian sistem integrasinya. Kajian ini menganalisa kesan penggunaan Penyerap Getar Dinamik Tertala dengan pembolehubah kekuatan berlainan (besi tahan karat, aluminium, loyang dan titanium) terhadap struktur motor-alur tak seimbang. Frekuensi asli rasuk diukur menggunakan Eksperimen Analisis Modal bagi membolehkan pemahaman terhadap tingkahlaku dinamik rasuk itu sendiri sebelum pengaplikasian Penyerap Getar Dinamik Tertala. Eksperimen Bentuk Defleksi Operasi dilakukan dalam arah paksi z dengan tiga kelajuan motor yang berbeza; 880 RPM (14.8 Hz), 2100 RPM (35 Hz), dan 2800 RPM (46.5 Hz) untuk mengukur getaran rasuk ketika motor beroperasi. Seterusnya, Penyerap Getar Dinamik Tertala yang terdiri daripada dua jisim sekunder digunakan untuk mengubah tindak balas dinamik struktur rasuk. Jarak kedudukan jisim Penyerap Getar Dinamik Tertala disesuaikan berdasarkan kelajuan motor untuk mengoptimumkan pengurangan getaran pada rasuk. Pemilihan bahan pemegang Penyerap Getar Dinamik Tertala disesuaikan dengan kepelbagaian ketumpatan, modulus keanjalan dan kapasiti keupayaan redaman yang menunjukkan kesesuaiannya terhadap frekuensi operasi dan keadaan tertentu. Pelbagai bahan pemegang Penyerap Getar Dinamik Tertala digunakan untuk menentukan penyerapan getaran yang paling berkesan dan didapati bahawa pemegang aluminium menghasilkan penyerapan tertinggi sebanyak 93.18 % pada kelajuan motor 2880 RPM. Selain itu, sistem pemantauan berasaskan keadaan kos rendah dibangunkan menggunakan pengawal mikro Arduino Uno yang dihubungkan ke Raspberry Pi. Sistem ini menggunakan penderia MPU9250 yang kos efektif dan sesuai untuk pengukuran getaran. Papan pemuka sistem dihoskan menggunakan pengkomputeran awan membolehkan akses masa nyata kepada data getaran. Sistem ini menggunakan empat keadaan boleh atur cara untuk terus menilai aktiviti getaran. Pendekatan yang mampu milik ini menawarkan penyelesaian yang mudah diakses untuk industri kecil seterusnya mengurangkan kebergantungan pada sistem penganalisis gred industri yang mahal. Sekiranya terdapat getaran tidak normal sistem boleh menghantar isyarat amaran yang berfungsi sebagai langkah pencegahan terhadap kegagalan struktur. Dapatan ini menyumbang kepada aplikasi yang lebih luas, termasuk penambahbaikan strategi penyelenggaraan dalam pelbagai industri, menitikberatkan kesan transformasi daripada gabungan kawalan getaran yang berkesan dan sistem pemantauan berkos rendah. Penyelidikan ini menyumbang kepada pemahaman tentang kesan bahan pemegang Penyerap Getar Dinamik Tertala yang berbeza terhadap kawalan getaran struktur rasuk dengan pendekatan praktikal untuk pemantauan keadaan masa nyata bagi meningkatkan kebolehpercayaan sistem.

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ABSTRACT

Unbalanced motor is referred to the situation of a rotating system where there is an uneven distribution of mass, resulting the significant vibration or imbalance problems. Poor management of unbalanced motor can lead to various issues, such as increased vibration, decreased efficiency, and potential damage of both motor and the integrated system. This study investigates the performance of reduction vibration for an integrated unbalanced motor-beam structure using a Tuned Dynamic Vibration Absorbers (TDVA), with different types of TDVA stiffness (stainless steel, aluminium, brass and titanium). To gain a better understanding of the system dynamic behavior, the natural frequencies of the beam were determined using an Experimental Modal Analysis prior to implementing the TDVA. The Operational Deflection Shapes (ODS) experiment was conducted in the z-axis direction with three different motor speeds; 880 RPM (14.8 Hz), 2100 RPM (35 Hz) and 2800 RPM (46.5 Hz) to observe the most significant vibration of the beam during operation. Later, the TDVA which consisted of two secondary masses, was employed to modify the structural dynamic response of the beam. The lengths of the TDVA masses were adjusted based on the motor speed to optimize vibration reduction of the beam. The selection of TDVA stiffness materials was driven by their varying densities, moduli of elasticity and damping capacities, providing insight into their suitability for specific operating frequencies and conditions. Various TDVA stiffness materials were applied to determine the most effective vibration attenuation and it was found that aluminium

material has produced the highest attenuation of 93.18 % at motor speed of 2880 RPM. Furthermore, a low-cost condition-based monitoring (CBM) system was developed using an Arduino Uno microcontroller connected to a Raspberry Pi. This system utilized an MPU9250 sensor which is cost-effective and appropriate for vibration measurement. The CBM system dashboard was hosted using the cloud, allowing real-time access to the vibration data. The system employed four programmable conditions to continuously assess the vibration activities. This affordable approach offers an accessible solution for small-scale industries, reducing reliance on expensive industrial-grade analyzers. In the event of abnormal vibration, the CBM system can trigger a notification alert, serving as a preventive measure against structure failures. The findings contribute to broader applications, including the improvement of maintenance strategies across various industries, emphasizing the transformative impact of combining effective vibration control and low-cost monitoring systems. It is also contributes to the understanding of the effect of different TDVA stiffness materials on the vibration control of beam structures with the additional of practical approach for real-time condition monitoring to improve system reliability.

CHAPTER 1

INTRODUCTION

1.1 Overview

The thesis investigates the vibration of an integrated unbalanced motor-beam structure, developing the low-cost Condition Based Monitoring (CBM) system and applying the Tuned Dynamic Vibration Absorber (TDVA) to reduce the vibration of the beam which subjected to different material stiffness. Through this chapter, a brief explanation on the CBM, unbalanced motor-beam and TDVA are explained. Consequently, the issue on monitoring of vibration of unbalanced motor is highlighted in the problem statement. Then, the research objectives, research scope, research gap and the limitation will be discussed as well. The outline of the research is presented at the end of this chapter.

1.2 Condition Based Monitoring (CBM)

Increasing machine equipment dependability to reduce downtime is an ongoing objective in manufacturing. But regardless of how perfectly a machine is constructed, wear and tear will always occur over time. CBM has thus been put in place to guarantee that the physical assets continue to operate with a high degree of dependability. The goals of machine condition monitoring research are to identify the health status of individual machines or the production system, identify the underlying cause of anomalies and stop failures before they happen (Haiyue et al., 2022).

The concept behind data-driven CBM is to define the job as a classification and link data-embedded information to different fault kinds and severity levels. In the past, to enhance model performance for defect detection, researchers have blended machine learning approaches with data or signal processing techniques (Compare et al., 2020).

Predictive maintenance is one of the most discussed topic in Industry 4.0. It uses CBM data to detect abnormalities in production processes, manufacturing equipment and products as well as diagnose and forecast them. The capacity to complete these jobs accurately enough offers the chance to establish just-in-time, just-right and efficient maintenance solutions. That is, delivering the appropriate part at the appropriate time to the appropriate location. This is a significant potential as it would optimise production profits while minimising expenses and losses. Figure 1.1 presents a framework for an Industry 4.0 Intelligent Manufacturing System (IMS) that incorporates CBM as a key element of its smart monitoring capabilities.

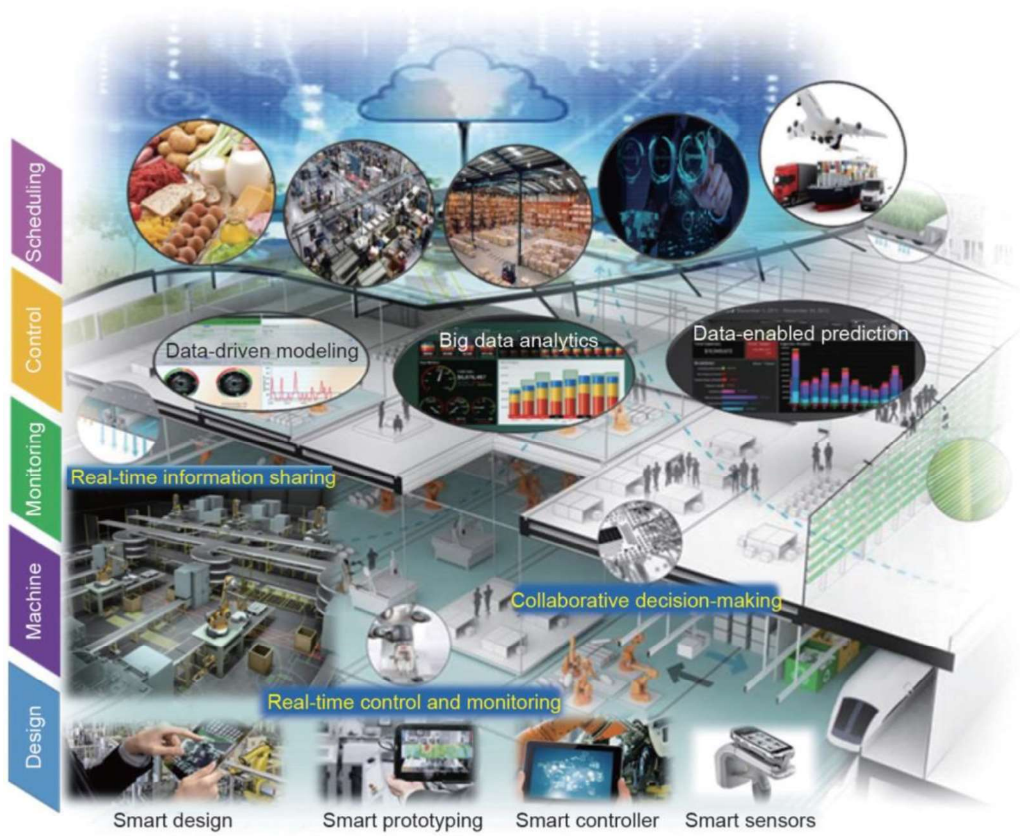

Figure 1.1 The framework of CBM in IMS (Zhong et al., 2017)

Vibration signals can accurately represent the dynamics of rotating machines like motors, bearings and gear boxes. They have been employed as one of the most useful CBM metrics. Time-frequency analysis, which may be converted into two-dimensional graphic pictures, is frequently used to study vibration signals. But regardless of the exact strategy used, all data-driven CBM approaches operate under the premise that every scenario involving the monitored equipment has already been recorded. Stated otherwise, the historical data and the monitored data have the same statistical distribution (Jay et al., 2014).

1.3 Unbalanced Motor-Beam

Unbalanced motors are commonly used in various mechanical systems to produce rotational motion. They are found in engines, turbines, pumps and other rotating equipment. In many applications, unbalanced motors are used to generate power by converting various forms of energy into mechanical energy, which is then used to perform specific tasks or drive machinery. Unbalanced motors are chosen for their ability to provide specific levels of torque, speed and power output, making them suitable for different applications where precise control over rotational motion is required.

The most prominent characteristic of unbalanced motors is the vibration they produce due to the uneven distribution of mass. This vibration can cause operational issues, decrease efficiency and potentially lead to damage because the vibrations produced can lead to premature wear and tear on mechanical components including the beam attached to it resulting in increased maintenance costs and downtime. Unbalanced motors tend to operate less efficiently compared to balanced systems because of the additional energy required to overcome the vibrations and maintain stability.

It is often produce more noise during operation compared to balanced systems, which can be undesirable in certain applications where noise levels need to be minimized. According to the data presented by Asim et al. (2023) in Table 1.1, the noise level in the unbalanced motor is observed to be 6.5% higher than that in the balanced motor. Due to their inherent imbalance, these motors require regular monitoring and maintenance to ensure optimal performance and to prevent issues such as bearing wear, shaft misalignment and structural damage.

Table 1.1 Noise measurement both balanced and unbalanced motor in different speeds (Asim et al., 2023)

Speed RPM	**Noise**	
	dB	**dB**
	Unbalanced	**Balanced**
600	67	67
900	73	71
1200	78	74
1500	81	76
1800	82	78

The beam that holds the motor plays a crucial role in supporting and stabilizing the motor within a system. However, when dealing with an unbalanced motor, the impact of the beam becomes more pronounced due to the dynamic forces induced by the imbalance. The beam can act as a conduit for transmitting vibration from the unbalanced motor to other parts of the system. This transmission of vibration can lead to unwanted oscillations in connected components, potentially affecting the overall performance and reliability of the system.

The presence of an unbalanced motor can excite natural frequencies of the beam and associated structures, leading to resonance phenomena. This resonance can amplify vibration levels, causing structural fatigue and potential damage over time. The dynamic stability of the beam-motor system may be compromised due to the presence of imbalance-induced forces. This can result in increased dynamic deflection and oscillations, affecting the precision and accuracy of the machinery.

1.4 Tuned Dynamic Vibration Absorber (TDVA)

TDVA plays a crucial role in mitigating vibrations and enhancing the stability of mechanical systems across a wide array of industries. These absorbers are engineered with adjustable parameters, including mass, stiffness and damping properties, enabling them to effectively counteract vibrations originating from rotating machinery or external forces. By precisely tuning the absorbers to target specific frequencies, they can effectively dampen vibrations and minimize the risk of structural resonance, thereby reducing the potential for damage and enhancing overall system performance and longevity.

Research efforts in the field of TDVA are multifaceted, encompassing various aspects of optimization, experimental validation and comparative analysis. One key focus of research involves optimizing the parameters of TDVA to achieve optimal vibration reduction across a range of operating conditions. This optimization process typically entails extensive computational modelling, simulation studies and experimental testing to determine the most effective combination of mass, stiffness and damping characteristics for a given application. Özer et al. (2015) developed a laboratory prototype for their study, consisting of a cantilevered flexible beam, an electric motor with an unbalanced rotor and an absorber. The 3D schematic of the experimental setup is shown in Figure 1.2.

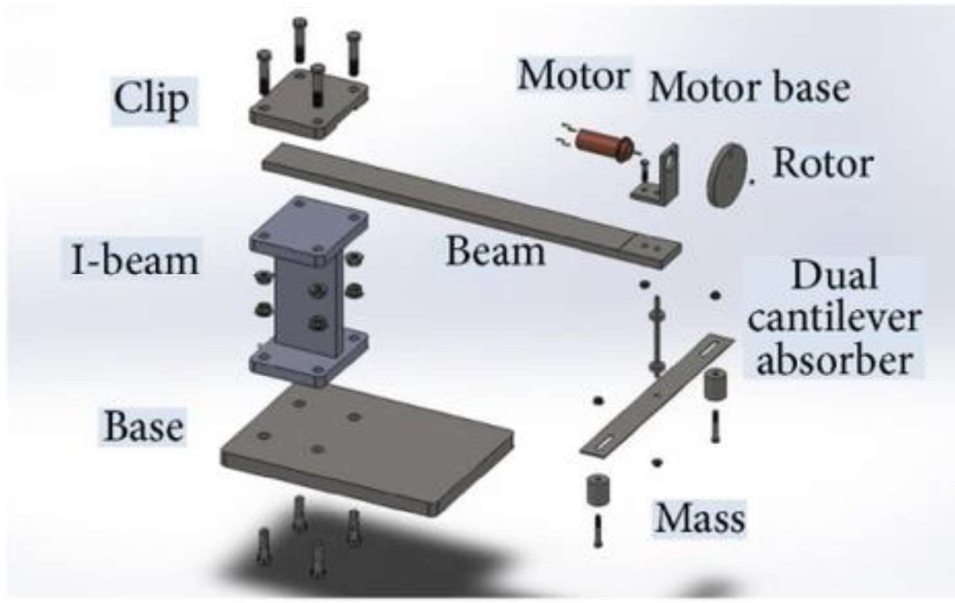

Figure 1.2 3D schematic view of an experimental setup to measure vibration with attached TDVA (Özer et al. 2015)

Furthermore, experimental validation plays a vital role in assessing the real-world performance of TDVA. Researchers conduct modal analysis, finite element analysis (FEA) and field testing to validate the effectiveness of TDVA designs in reducing vibrations and improving system stability. Through rigorous experimentation and validation, researchers gain valuable insights into the practical limitations and performance capabilities of TDVA, enabling further refinement and optimization of these vibration control devices.

Moreover, comparative studies are conducted to evaluate the relative advantages and limitations of TDVA compared to other vibration control methods, such as passive dampers, active control systems and tuned mass. These comparative analyzes provide valuable insights into the strengths and weaknesses of different vibration control techniques, helping engineers and designers make informed decisions regarding the selection and implementation of vibration mitigation strategies in various industrial applications.

1.5 Problem Statement

In manufacturing and industrial settings, the management of unbalanced motors poses a significant challenge due to its potential ramifications on system performance and reliability. Inadequate control over these motors frequently results in increased vibration, reduced performance and increased mechanical failure risk, which negatively affects the motor and the entire system. This study seeks to address this critical issue by investigating the efficacy of employing TDVA as a means of reducing vibrations within an integrated unbalanced motor-beam structure.

Specifically, the research aims to assess the effectiveness of TDVA with varying stiffness materials, including stainless steel, aluminium, brass and titanium, in mitigating the deleterious effects of motor imbalance. By comprehensively evaluating the performance of TDVA across different stiffness materials, this study endeavours to provide valuable insights into optimizing vibration control strategies for enhancing the stability and reliability of mechanical systems operating with unbalanced motors.

Furthermore, this research will explore the implementation of CBM systems capable of continuously tracking and analyzing vibration data, facilitating the prompt detection of imbalance conditions and performance deterioration. Existing CBM systems are often expensive, requiring high upfront costs for installation as well as ongoing maintenance and operation costs. For example, industrial-grade CBM systems can cost thousands of dollars due to their advanced sensors, data processing units and specialized software for real-time analysis. Such costs can be prohibitive for small to medium sized enterprises, where budget constraints are a significant concern. For instance, CBM systems like the SKF IMx or Schaeffler's FAG SmartQB can cost upwards of USD 10,000 to 20,000, which is approximately RM 47,000 to RM 94,000. These high costs make them impractical for widespread use in cost-sensitive applications.

This study aims to explore the integration of a low-cost CBM system to continuously assess the vibration of unbalanced motor-beam structures. The primary problem being solved is the lack of affordable, real-time, actionable data on motor vibrations, which hinders effective maintenance and timely intervention. The developed low-cost CBM system utilizes an Arduino Uno microcontroller and an MPU9250 sensor, offering a much more affordable alternative to traditional systems, while still being capable of monitoring vibrations and triggering alerts when abnormal conditions are detected.

Moreover, many existing monitoring systems do not provide real-time monitoring or require periodic inspections, which can delay the detection of faults or imbalances. Traditional methods often rely on offline measurements or scheduled inspections, where vibration data is collected at fixed intervals, limiting the ability to detect abnormal conditions immediately. This results in increased risk of system failure, downtime, and costly repairs.

The system’s real-time capabilities allow for continuous monitoring of the system's condition, improving reliability, supporting predictive maintenance, and reducing downtime without the prohibitive costs associated with high-end systems. By making CBM accessible and affordable, this research demonstrates how such systems can be implemented even in smaller or budget-constrained environments, thereby preventing motor damage, reducing maintenance costs, and enhancing system longevity.

1.6 Research Objectives

In this study, the following objectives are set to be achieved:

(a) To develop a low-cost portable vibration analyzer with a CBM system using Arduino based accelerometer for continuous vibration monitoring of the unbalanced motor-beam.

(b) To analyze the vibration characteristics of the unbalanced motor-beam at low, medium and high speeds, focusing on frequency and amplitude to identify critical operational thresholds.

(c) To analyze the performance of TDVA in reducing the vibration of unbalanced motor-beam using different stiffness materials.

1.7 Research Contribution

This study makes a substantial contribution to the field of mechanical engineering by tackling the issues related to unbalanced motor-beam systems through the development of a low-cost portable vibration analyzer and applying the TDVA with different stiffness materials. The development of the vibration analyzer, utilizing an Arduino based accelerometer, constitutes a noteworthy contribution to the field. It provides a cost-effective and accessible tool for assessing and monitoring vibrational behaviour in real world applications. Through the integration of user-friendly interfaces and the utilisation of readily accessible components, the developed analyzer facilitates widespread adoption among engineers and practitioners, thereby enabling proactive maintenance strategies to mitigate the detrimental effects of unbalanced motors on system performance and reliability.

Furthermore, the comprehensive analysis of TDVA constitutes a significant advancement in vibration reduction techniques for mechanical systems. Through systematic experimentation, this research evaluates the effectiveness of TDVA in attenuating vibrations within unbalanced motor-beam systems. By considering various TDVA materials, including stainless steel, aluminium, brass and titanium, the study offers valuable insights into the influence of material properties on vibration reduction performance. The findings provide practical guidance for engineers in selecting and implementing TDVA solutions tailored to specific application requirements, thereby contributing to the advancement of vibration control methodologies in industrial settings.

1.8 Scope of Research and Limitation

This study aims to investigate the vibration characteristics of an integrated system consisting of an unbalanced motor attached on a beam structure rig. Measurements will be conducted on a rig structure representative of the integrated system, allowing for controlled experimentation. The analysis will focus on vertical vibrations in the z-axis direction and will include measurements at three different motor speeds to assess the influence of operational conditions on vibration behaviour. Additionally, the study will evaluate the effectiveness of TDVA constructed from four different materials (stainless steel, aluminium, brass and titanium) in reducing vibrations within the integrated system.

Several limitations are acknowledged within the scope of this research. Firstly, Firstly, the unbalanced motor introduces a significant constraint on speed control. Due to the rotor's imbalance, the regulator cannot effectively adjust the speed across the entire desired range. Therefore, selecting an appropriate tuning speed for the motor becomes crucial. Secondly, constraints on the length of the TDVA mass's beam may limit its ability to effectively target specific vibration frequencies. This constraint arises from the size of the experimental rig, which imposes a maximum beam length of 300mm. Any longer, and the TDVA would not be able to be mounted securely. Additionally, the fixed mount point of the TDVA on the beam structure may limit optimization for maximum vibration reduction. Lastly, the reduced sampling rate for data transmission to the cloud for real-time condition monitoring may affect the accuracy of vibration data analysis. These limitations should be taken into account when interpreting the research findings and implications.

1.9 Thesis Outline

This thesis comprises five primary chapters, including the introduction, literature review, methodology, results and analysis, as well as conclusion and recommendations.

The first chapter explains the brief introduction of the research including the concept of CBM and its implementation in the 4th Industrial Revolution era. This chapter also briefly explained the concept of unbalanced-motor and its impact to the integrated system set as well as the implementation of TDVA. The problem statement, objectives, research contribution and the scope of research and limitations also explained in this chapter.

In Chapter 2, an extensive literature study is presented. First, the specific attributes of CBM are looked into. Next, this chapter presents a comprehensive analysis and review of the integrated system of an unbalanced motor. Subsequently, various techniques for measuring vibrations using different accelerometers are presented. Following that, a comprehensive explanation of prior studies on vibration analysis, encompassing both frequency and time domains are included. This chapter also presents the implementation of micro-electro-mechanical systems (MEMS) sensors. The Structural Dynamic Modification (SDM) and TDVA approaches are thoroughly discussed with a particular focus on evaluating the efficacy of their use as demonstrated in prior research. Finally, this paper explores the application of CBM using the Arduino-based system and the open-source Node-RED.

Chapter 3 presents the methodology used in this research. Firstly, an explanation is provided on the development of vibration analyzer for CBM. Subsequently, the arrangement of the experimental apparatus is introduced. The present study demonstrates several vibration analysis techniques such as Experimental Modal Analysis (EMA), Operational Deflection Shapes (ODS) as well as the utilisation of vibration measuring methods that encompass standard approaches to vibration measurement. In addition, the theoretical model and vibration measurement methods utilising TDVA implementation are also presented.

In Chapter 4, the findings derived from the vibration measurement and analysis were elucidated. Firstly, the natural frequencies, the mode shapea and the Frequency Response Function (FRF) from the EMA are showed. Subsequently, the vibration measurement outcomes of the beam are displayed in both time and frequency domains. Finally, the vibration results after the TDVA implementation on each different stiffness materials as well as the three different motor speeds are presented and discussed.

Chapter 5 provides a concise overview of the study's findings and presents recommendations for future research advancement.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter presents a comprehensive literature review, which explores the pivotal aspects of the research. Firstly, the literature review elaborates on the principles of CBM and how it is utilized to detect changes in vibration patterns, signifying potential wear or faults within mechanical systems. Secondly, the review addresses the crucial aspect of data transmission within CBM ecosystems. The third section of the review delves into the specific challenges associated with the vibration of unbalanced motors and the consequent impacts on their integrated systems. Subsequently, the literature evaluates the application of MEMS accelerometers for vibration analysis, underscoring their suitability due to their compactness, sensitivity, and reduced power consumption. Further elaboration is made on the integration of the MPU9250 accelerometer with the Arduino Uno microcontroller. The utilization of Raspberry Pi for CBM is yet another emerging trend detailed in this chapter, highlighting its capabilities to serve as an affordable and versatile platform for vibration monitoring systems. Complementing the hardware components, the chapter proceeds to review the Node-RED programming tool, offering insight into its contribution to CBM systems as a visual development tool to wire together hardware devices. Lastly, the literature review assesses the role and functionality of the TDVA. Its significance in vibration suppression and the theoretical frameworks alongside practical applications of TDVA in engineering are meticulously examined.

2.2 CBM for Vibration

In recent years, vibration-based condition monitoring of mechanical structures and machinery has become a well-established technique (Kamariotis et al., 2022). In their operational environment, mechanical components like wind turbine blades and shafts will unavoidably experience vibrations (Davoodi et al., 2023). The inherent signals that these vibrations carry in the temporal and spatial domains allow for the identification and localization of structural feature changes. The purpose of assessing the structural health of civil engineering structures like bridges, vibration-based detection techniques are also widely used (Saidin et al., 2022).

Vibration signal analysis is a crucial tool in CBM, as vibrations can be indicative of many potential issues within machinery. A study entitled by Cui et al. (2021) states that vibration signal analysis is the most widely used method due to its high diagnostic accuracy. Signal processing technology and the application of artificial intelligence for pattern recognition in fault diagnosis are key areas of research in this field. Konstantinova et al. (2022) discusses the main cause of fluctuations and oscillatory processes in asynchronous motors which is dynamic loads. This underpins the importance of considering such dynamic occurrences in developing CBM strategies.

The utilization of CBM is a method employed to execute condition-based maintenance for machinery that experiences vibrations. This methodology entails the acquisition of data from several sensors, including vibration sensors, noise sensors and temperature sensors, followed by its analysis to ascertain the state of the machinery (Zhao, 2021). An emerging theme in recent literature is the advancement in sensor technology and its application in CBM. Jiang and He, (2020) analyze the role of sensor technologies in construction machinery for monitoring conditions, including vibration sensing. The capability of these sensors to provide real-time, continuous data has significantly augmented CBM's efficacy. Figure 2.1 shows an illustrative instance of a vibration monitoring system that has been implemented in an electrical rotating machine with the purpose of facilitating predictive maintenance.

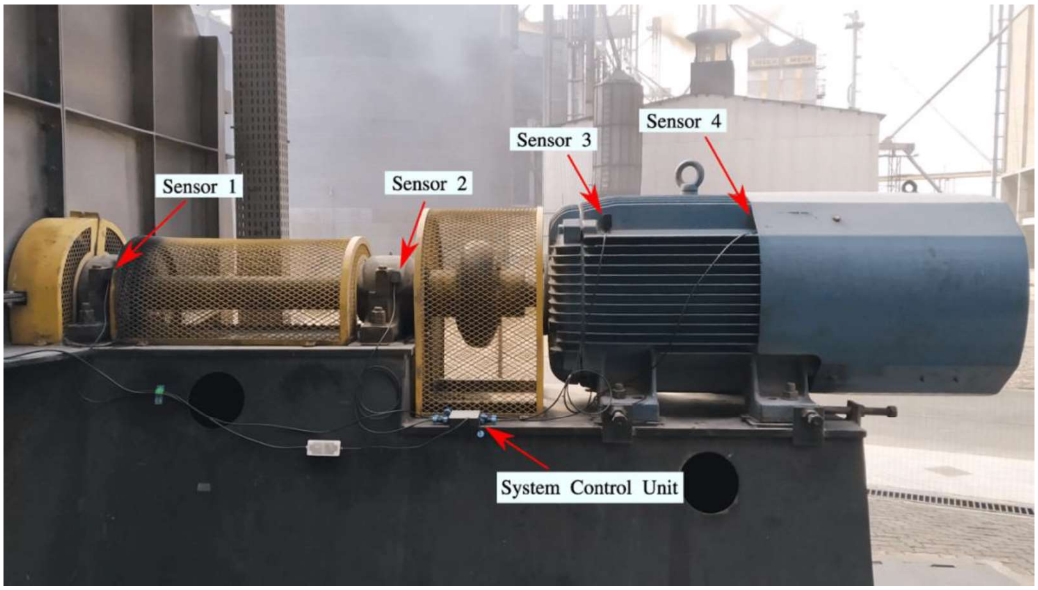

Figure 2.1 Example of vibration monitoring system installed in an electrical rotating machine for predictive maintenance (Romanssini et al., 2023).

The objective of CBM is to anticipate the deterioration of equipment components and their potential for unforeseen malfunctions, enabling timely maintenance to be carried out. Implementing this measure can effectively mitigate expensive periods of inactivity and equipment harm, while also enhancing the productivity and dependability of the machines (Gullo & Kovacevic, 2021).

Maurya et al. (2020) provide valuable insights into the use of one-dimensional convolutional neural networks for real-time motor condition monitoring and fault detection. Their research suggests the viability of real-time analysis, which is vital for

CBM. This aligns with practical cases such as a study demonstrates the successful implementation of real-time CBM strategies to mitigate equipment vibration in a cement plant environment (Zhu et al., 2020).

In a different domain, the concept of CBM through vibration analysis can also be extended to areas such as healthcare equipment monitoring. "IoT-Based Coma Patient Monitoring System" discusses a system evaluated via a case study concerning continuous patient monitoring to early-detect patient deterioration through vibration analysis of the vital sign (Yimer et al., 2024). Advanced monitoring systems have the capability to evaluate the seriousness of faults and pinpoint the precise components that are not functioning properly. In contrast, predictive maintenance systems utilise sensor information to approximate the remaining useful life (RUL) of the machine or system. Figure 2.2 summarized the different between CBM and predictive maintenance system.

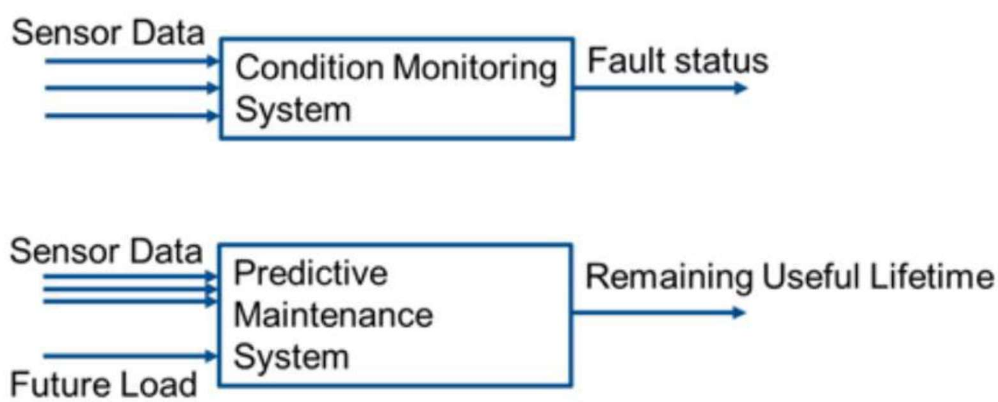

Figure 2.2 The function of CBM and predictive maintenance system (Martin et al., 2018)

Previously, CBM has frequently entailed a review of time and frequency domains. These methodologies cover an analysis of the temporal dynamics of the sensor data and the frequency components of the data, respectively, in order to detect patterns and trends that could potentially signify machinery-related problems (Liu et al., 2021). However, with recent advancements in technology and the maturity of research in vibration signal analysis, CBM based on vibration signals has become a preferred method due to its ease of implementation and the availability of relevant research.

The analysis of mechanical flaws in vibrating machinery can be facilitated through the utilization of vibration spectra, which enable the identification and differentiation of the equipment's vibration signature. The signature refers to the recurring vibration pattern that is distinctive to a specific mechanical defect. The rapid and precise diagnosis of prospective equipment concerns can be achieved by comparing the vibration signature of the machinery with established signatures of typical mechanical flaws, including bearing failures, mechanical imbalance and gear faults (Ahmed et al., 2023).

Lin et al. (2023) address controversial cases in rotor condition diagnosis, where classical methods have failed due to the variable nature of driven loads. This underscores the challenge of adapting vibration analysis methods and CBM to more complex and dynamic operating environments.

The selection of a sensor for a CBM system is contingent upon the purpose of the system and the particular attributes that necessitate monitoring. In the context of vibrating machinery, it is standard to utilize displacement, speed and acceleration sensors for the purpose of evaluating the vibration levels shown by the equipment. It is crucial to distinguish between the distinctive patterns of data in the time and frequency domains during the initial phases of CBM (Jiaxing et al., 2021).

The identification of faults is of utmost importance, as various fault types will manifest distinct patterns within the temporal and spectral domains. Consequently, a multitude of techniques have been devised to conduct defect identification through the comparison of outcomes in both the temporal and spectral domains. The method of fault diagnostic is outlined in Figure 2.3.

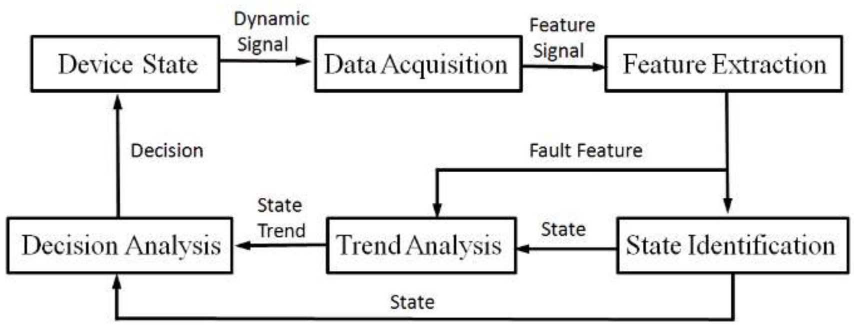

Figure 2.3 The process of fault diagnosis (Duan et al., 2018)

2.3 Data Transmission in CBM

The reliable storage and transmission of measurement data is essential for the permanent or long-term measurement of vibration in rotating machinery. The establishment of communication between measuring equipment for the transmission of vibration data can be achieved through various methods. Communication can occur either directly from the device/sensor to the Internet, where the data is saved for subsequent analysis, or indirectly from sensor to the end device, without requires Internet connectivity (Yu et al., 2023). Industry 4.0, often known as the 4th Industrial Revolution, is predicated around the principles of automation and digitization. This encompasses the implementation of the IoT, exchange of information between machines, enhanced transmission and communication of data as well as monitoring depending on specific conditions (Sicard et al., 2022).