USE OF VIBRATIONS ANALYSIS TECHNIQUE IN CONDITION BASED MAINTENANCE

Master of Science Thesis in the Master Degree Programme Production Engineering and Management

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Abstract

Condition based maintenance, CBM, means that an a priori defined; preventive task is performed at certain condition of the equipment. This strategy is much more cost effective than maintenance on failure or scheduled maintenance. When running to failure, an unplanned interruption to production or service is induced. Also a collateral damage may occur, leading to costly consequences. Extensive spare parts inventory has to be kept in place as well. Scheduled preventive maintenance results usually in repairing or replacing components too early or too late, leading in a maintenance that is to expensive and ineffective in preventing breakdowns.

To improve availability, the system is redesigned for higher reliability and the need for maintenance is minimized. The maintenance is also be carried out in more effective manner, and in a planned way. Finally, some condition indicators are monitored to observe deterioration and detect onset of failures.

This project is aimed at analysis of MAZAK 3-axis CNC milling machine, and identifying possible condition indicators based on vibration measurements and analysis.

The construction and operation of a MAZAK 3-axis CNC milling machine is available from an operating manual. An extensive literature study has been done to come across with the state of the art in vibration based analysis of machine tools, and the goal is to go beyond the state of the art. Extensive practical vibration measurements are performed in the laboratory and analysis is done in matlab.
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1. INTRODUCTION

1.1 BACKGROUND

Need for Plant Maintenance

The maintenance management was taken up as a serious issue only after the dynamic industrial revolution during the Second World War (Vyas & Pophaley, 2010). Rapid modernization and the increasing need for high yielding productivity have led to finer development and use of hi-tech and complex machines and equipments. Therefore, high cost capital is involved in the production shop floor and the occurrence of incipient and frequent failures may result in production downtime and huge losses for the enterprise. Hansen I.H, in his paper, referred that maintenance cost can be the second largest part of organizational budget, next to only energy costs (Hansen, 2006). So, controlled and appropriate maintenance activities are required which will minimize the occurrence of such failures and increase the reliability of the factory assets through effective plant maintenance practices.

Condition based maintenance (CBM) or Predictive maintenance (PdM) can be best described as maintenance practiced when need arises (Morales, 2002). This is done by monitoring the condition of the machine (or equipment) continuously or periodically depending upon the need for the availability of the machine.

The maintenance is initiated when indicators show the sign of faults in the incipient stages. In simple words, the main criterion is to maintain the right equipment at the right time. The practice of CBM is done by acquiring and analyzing the real time data, so that maintenance activities and resources can be prioritized/optimized accordingly. (Morales, 2002)

Vibrations analysis technique

In today’s times 80% of the parameters measured likely to be, vibrations based (Vyas & Pophaley, 2010). Hence, Vibrations monitoring and analysis is also one of the most widely used technique in condition based maintenance and rely a lot on instrumentation Machine vibrations stack a lot of information about the condition of a machine. Measurement and analysis of the vibration response gives a lot of information with relevance to fault conditions in different types of machines (Khwaja, Gupta, & Kumar, 2010).

Vibration-based analysis techniques can be widely used for condition based maintenance because vibration spectrum can be collected for all machinery which consists of rotating or moving elements. Vibration analysis is one among a number of techniques in condition based maintenance employed to monitor and analyze certain machines, equipment, and systems in a plant. Nevertheless, the prime notion behind the use of vibration analysis is to monitor rotating machinery to detect growing problems and to eradicate the possibility catastrophic failure. This is the most commonly used maintenance practice applied in strategic maintenance systems.

1.2 Purpose

The master thesis is carried out at the department of Industrial Engineering and Management at KTH. The idea behind this master thesis is to improve the overall availability by designing/redesigning the system for higher reliability and minimize the need for maintenance.
Condition signatures of a machine, are to be monitored to observe and correlate deterioration and faults to detect the possible failure in the incipient stage. The expected outcome is to improve the reliability of fault detection and analysis.

1.3 Research Question

To have a better understanding of the challenge to succeed, the purpose is broke down into three research questions. By solving these questions using current state of the art techniques in vibrations analysis technique in CBM, we can come up with solutions that are more robust

1. **What** variables are to be measured and analyzed and **what** components shall be a part of the system
2. **How** to come up with state of the art technique with extensive literature review
3. **How** shall the system be designed/redesigned to improve the reliability

1.4 Delimitations

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<tr>
<td>1.</td>
<td>The project will only consider MAZAK CNC milling machine. However the method is applicable to any other heavy machine</td>
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<td>2.</td>
<td>Components which are not directly relevant with maintenance practicum are not considered</td>
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<td>The time limit for the project is 800 man hours</td>
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Table 1. Delimitations

1.5 Report Structure

The structure of the report follows a pedagogical and organized pattern with clear collocations, so that the reader gets a comprehensive understanding of the thesis. The thesis report starts with a short explanation about the research methodology (procedures) adopted for answering the research questions in step by step manner to achieve the objective of the thesis. It is followed by a detailed theoretical framework to offer the reader is well versed about the subject chosen and to demonstrate that the author has a sound knowledge and understanding of the theories. The third chapter describes the case studies, which is an adopted research methodology to gain in depth and longitudinal examination about the subject. The next chapter progress to relevant description and evaluation of milling machine selected for the experiment, which include design and operation and the core information about the experimental setup which includes the details about hardware and software used for acquiring and cleansing relevant data. The next chapter will include the implementation of the state of the art techniques which were reviewed in the theoretical framework section for the analysis of the obtained data. The report will be finalized with discussions of the results gained after the analysis which eventuate to the conclusions also containing possibilities for the future work.
1.6 Methodology

![Diagram of thesis work phases]

*Figure 1: Thesis work phases*
2. THEORETICAL FRAMEWORK

2.1 Plant Maintenance practices

Plant Maintenance is the subject that has gradually progressed simultaneously with development in Industrial Engineering and Management. In earlier times, it was termed as ‘necessary evil’ in production environment as described by (Jayantha, 2010). The new ‘leaner and waste free’ production systems evolved over the years and are currently in vogue these days, has tremendous impact on the maintenance process. The whole perspective about the significance of plant maintenance systems has been changed from ‘necessary evil’ to ‘fruitful function’. Hence forth the maintenance management programs and methodologies are more strategized, so that it can reap benefits for an organization in various ways.

Maintenance is defined as

“A combination of all technical administrative and managerial actions during the life cycle of an item intended to retain in it, or restore it to a state in which it can perform the required function” (EESTI STANDARD, 2010)

Plant Maintenance in general, refers to overall maintenance activities carried out in an industrial factory ranging from periodic checkups of the equipment to make sure that they are running resourcefully to cleaning up other mess around the premises. The main objective of plant maintenance is to develop and sustain a highly productive and safe working environment. The maintenance practices, strategies and methodologies may change from company to company. For example, maintenance methods in steel industry may have different work plans than food industry or IT consultancy. The maintenance management schemes and strategies are customized to the requirement of the enterprise.

The plant maintenance function has to ensure that the item provides the relevant information, fulfils the requirement of health and safety during the operations and influence on environment is within the acceptable realms. To define an efficient maintenance strategy in detailed way, it can be broken down in three main criteria

- To ensure the ‘availability’ for a particular function at most optimum cost
- To guarantee the safety of working personnel associated with maintenance tasks and make sure that it has tolerable impact on the environment
- To sustain the dependability of an item by improving the ‘reliability’, ‘maintainability’ and ‘supportability’ of the equipment, this in turn, increases the overall availability.
To explain the concepts of plant maintenance in better way, one needs to get familiarized with the following terms:

AVAILIBILITY: It can be defined as the degree to which equipment is in a specified operable and performable state for a defined function, when the function is called for. To define it in simpler way, it is a discrete proportion of time for which the equipment is in functioning state. According to Federal Standard 1037C public domain material of general services Administration-USA, it described as mission capable rate (Federal standard 1037C, 1996)

Barlow and Proschan (1975) define availability of a repairable system as "the probability that the system is operating at a specified time t." (Barlow & Proshcan, 1975). Blanchard [1998] gives a qualitative definition of availability as "a measure of the degree of a system which is in the operable and committable state at the start of mission when the mission is called for at an unknown random point in time." (Blanchard, 1998)

This definition comes from the MIL-STD-721. Lie et al [1977] developed a complete survey along with a systematic classification of availability. (Lie, Hwang, & Tillman, 1977)

\[
A = \frac{E[\text{Uptime}]}{E[\text{Uptime}] + E[\text{Downtime}]}
\]

RELIABILITY: It can be defined in several ways such as, the probability that the function will be performed by a specified unit under stated conditions in a specified period of time, or capability of a system or equipment to perform the functional task, or the resistance of a failure of system or equipment, or the notion that the specified thing is healthy for the job, and finally in few aspects it can also be defined as ability to fail without catastrophic outcomes.

The Following Graph is called as Bathtub curve hazard function which is used in the concept of Reliability to explain the pattern of failure rate versus time

The first part is decreasing failure rates popularly known as infant mortality

The second part is constant failure rates popularly known as random failures

The third part is an increasing failure rates popularly known as wear-out failures (Bathtub Curve, 2010)
Figure 2: Bathtub Curve (Bathtub Curve, 2010)

MAINTAINABILITY: In plant maintenance engineering, 'Maintainability' can be described as the easiness with which a system or equipment can be maintained in order to desolate defects and their causes, rectify the effects and their causes, accomplish new requirements, minimize the need for frequent maintenance in future, adapt to change in the environment. (Ebeling, 1997)

In different scenarios, maintainability can also correspond to a system of continuous improvement, i.e. to learn from the past in order to improve the ability to maintain systems, or optimize reliability of systems based on prior experience of maintenance methods. (Federal standard 1037C, 1996)

SUPPORTABILITY: It can refer to repair and troubleshooting on the job for a system or an equipment to ensure there is no hindrance during the operation and functioning of the system or equipment. Supportability can be executed either during the design and development of a new system or equipment by using design management techniques such as 'Design for maintainability' to enhance the maintainability in the future or it can be implemented during the operations to optimize the availability of systems or equipments in a cost effective manner.
Since many years and still the same for some plants, views about maintenance was that its function is only to keep the plant running. The general philosophy was if the machine failed, they were repaired or spare were used. Equipment reliability or prediction of the failures was not given much of a consideration. The maintenance department was looked upon as needless cost, and that was considered just a part of running the business. In order to achieve large margins of cost savings, a particular approach often termed as precision maintenance or proactive maintenance has been evolved.

When it comes to the maintenance costs, Mobley R Kieth (2002) says that maintenance is a major sect of total operational cost in the production plants and it can cover anywhere between 15 to 60 percent of the cost of the final product. Ranging from 15% [probably minimum] in the food industry to 60% [maximum] in heavy industries such as steel plant. The ineffective maintenance management, which can lead to loss of production time and poor product quality is more than 60 billion USD in US industry. This clearly shows the importance of maintenance management in the present industrial demands (Mobley, 2002)

To study how a method called Predictive maintenance or Condition based maintenance, which employs a particular methodology of Vibrations analysis to improve the overall reliability, maintainability and support, it is important to review other traditional maintenance techniques, so that the evolution of state of the art in CBM can be known.

There are three classifications of maintenance methods defined by DiLeo et al. (1999) which is depicted in the following figure (DiLeo, Manker, & Cadick, 1999)

![Maintenance Approaches](Image)

*Figure 3: Maintenance Approaches (Söderbäck & Östman, 2010)*
The maintenance activities carried out in a plant can be classified as follows

**Corrective maintenance or Breakdown maintenance**

Maintenance carried out after recognizing the fault and to restore the item in proper working condition again, so that it performs the required function. The general philosophy is "If it isn't broken, don't fix it." The shop floor where this kind of maintenance technique is implemented does not spend any money until or unless the system is down. Hence it can lead to high maintenance costs, unanticipated downtime and secondary damage to the machine, catastrophic consequences, unnecessary spares and lack of control.

The only advantage is it does not result in unnecessary maintenance, which can be a part of other maintenance management techniques.

**Preventive / scheduled / planned maintenance**

Maintenance performed on discrete regular intervals and aims to minimize the probability of failure and downtime. The basic theory is that the total life cycle of a machine is limited and probability of failures increases as age. So, we will perform maintenance before hand to avoid failure and to extend the life span of the machine.

However estimating the total life cycle of a machine is quite a challenge. Therefore the preventive maintenance methods vary from industry to industry. Usually a new machine has a high probability of failure when it is installed [refer figure 1] due to poor lubrication, incorrect parts installed and poor alignment and balance, etc.

The main advantages of this type of maintenance program are that the maintenance can be carried out in convenient time and in a controlled manner, random failures should be reduced resulting in lesser cataclysmic failures, reduced machine downtime and control over the spare parts stock level.

2.2 Condition based maintenance (CBM) or Predictive maintenance (PdM):

Maintenance carried out following a forecast derived from the analysis and implement

cause ↔ symptom ↔ effect to predict the need for action

The common principle of Condition based maintenance is that timely monitoring of the practical mechanical condition, operational efficiency, and few other indicators related to operating condition of machine-trains and process systems will provide the data necessary for ensuring the maximum time between repairs and minimize the number and cost of unscheduled interruptions caused by failures.

As the term suggests, Condition based maintenance is a condition-driven preventive maintenance program. Rather than depending on "mean-time-to-failure" (plant average-life statistics) to pre-plan maintenance activities, condition based maintenance uses on site monitoring of the mechanical condition, system efficiency, and other indicators to predetermine the actual mean-time-to-failure or loss of efficiency for the system or equipment in the plant. However, "Reliability Centered Maintenance" can be described as the final
decision whether to apply constant condition monitoring or preventive or run-to-failure programs on repair or rebuild schedules on the basis of intuition and the personal experience of the maintenance manager.

The advantages of such kind of new age maintenance method condition based maintenance include reduction in unexpected downtime, parts can be ordered and used on just-in-time principle and maintenance activities are performed only when they are called for, resulting in eradication of over maintenance. Whatsoever, the initial costs associated with condition based maintenance will be high as instruments, system, services and personnel involves a lot of money and there is no complete assurance that the machine life is extended after the plant adapts condition based maintenance.

If the knowledge acquired through apt condition monitoring is analyzed in a right way, the benefit gained by condition based maintenance is hugely effective. The possible benefits can be that the deterioration is treated before safety is questioned, production or process is halted and significant damage occurs. Maintenance is always performed when instantaneously needed leading to zero interference with production or process, less maintenance activities and expenditures and avoidance of low morale usually associated with unnecessary maintenance.

The integration between operations and maintenance is improved resulting in higher respect for maintenance personals in the plant, self esteem and high moral of associated work force, better handling of equipment and reduction life cycle costs of assets or system.

Condition based maintenance mostly relies on the tell tale signs before failure such as change in vibration level and pattern, Increased temperature of the parts, wear in the surface detected via analysis of lubricant, change in system performance, motor current change, etc. The task is to look for out for such signs using condition monitoring technique so that the risk of failure and maintenance costs, both decreases.

**Condition Monitoring**

Nonetheless, condition monitoring is widely implemented in condition based maintenance, if the signal based approach is implemented. The purpose of condition monitoring is to detect the incipience of deterioration and to provide a scale of extent and rate of deterioration to failure. In this context failure of a system may be caused by actual failure of equipment or by deterioration in performance to a level which is unacceptable for health, safety, environment and other factors.

Condition based maintenance depends widely on statistics and probability theory. Proper trend detection through analysis of data often rewards the analyst with to delve deeply into the causes of failure and preventive/corrective actions that will help avoid future failures. For example, decorative lights burn out quite soon when compared to, say street lights. If 12 percent of the lights have burned out, it may be accurately assumed that the rest will fail soon. They should be replaced most effectively as a group rather than individually.

Condition monitoring in effective way, does not necessarily mean the practical viability, selection and use of apt condition monitoring technique, but also upon the efficient management of the collection, storage and assessment of the measurable parameters. Condition monitoring can be justified for reasons of safety and economics and the validation is done by setting tailored strategies for each system or unit after assessment of reliability.
The costs of condition monitoring system basically incurs the costs for purchasing the condition monitoring equipment, hiring and training condition monitoring personnel, installation of the system, losses due to false alerts or missed failures, carrying out timely monitoring, analyzing the data and correlating the problems. Neale M.J [setting up a working condition monitoring system] concluded from his survey that the initial costs associated with condition monitoring systems, i.e. the cost of purchasing represents 40% of the total cost of setting up a condition monitoring system. 50-60% of the funding will be used for training, setting up and continuous improvements. (Neale, Setting up a working condition monitoring system, 1979)

Neale M.J et al also concluded in other paper ÔA guide to condition monitoring of machineryÔ that the savings per annum by introducing condition based maintenance to a plant were around 1.2% of the added value of the process. When condition based maintenance is introduced to only a part of the production process this same percentage return can be expected. When considered on individual asset, with correct introduction of condition based maintenance, the production losses can be expected to come down by 75% and on failure maintenance costs by 60%. In addition to this, there will also be maintenance cost reduction with elimination of unnecessary planned maintenance routines. (Neale, Woodley, & Woodcock, 1978)

Henry TA in his Bearing paper has quoted that a return on investment is 10 to 15 times the initial investment for the programs ranging from pilot projects setup and run on a handful of units by specialized consultant, to plant wide project covering a hundred or more units and run by an in house specialist team. (Henry, Baker, & Scott, 2009)

Procedures to ensure cost effective benefits

To assure the cost effective introduction of condition monitoring always estimate the would-be savings and calibrate the condition monitoring program to suit as follows.

1. Estimate for each of the modes of failure from the history logs that it is proposed to monitor the previous costs of production or service loss, maintenance before and after failure
2. Use the information to estimate probable saving over a period of time
3. Estimate the costs of installing the condition monitoring program for particular mode of failure and each unit, and select an appropriate approach that is expected to give an acceptable return on expenditure
4. This information can then be presented via project charter tool to obtain funding and permit to go ahead
5. Make cost benefit the highest priority during implementation
6. Provide hands-on training for all personnel expected to work with condition based alerts
7. Log all detections and their resulting actions including cost estimates, and report regularly to the concerned authority on the benefits achieved
8. Keep assessing the program at three levels
   - Routine monitoring organization for optimal use of human resources
   - Avoid false alerts and missed failures by application to correct modes of failures by most effective techniques
   - Increase the cost effectiveness of whole condition monitoring program
**Description of techniques**

The most common of types of techniques used in condition monitoring today include human senses which are visual observations, listening and touching. Such senses employ visual inspection, tactile inspection smelling, aural inspection and optical magnification. (implementation strategies and tools for condition based maintenance, 2007)

However, the value of observations is not limited to unmonitored equipment. Use of sensors to gather information may also be extremely valuable for data acquisition and analysis. It is highly recommended that personnel from both operations and maintenance department be trained observers as this particular piece of information will a provide a deeper and broader understanding of the machine condition

A comprehensive condition based maintenance program shall utilize variety of technologies. The majority of plant equipment constitute for mechanical systems, vibration monitoring is generally the key component of most condition based maintenance programs and is also the most widely used technique with 80% of the parameter measured are likely to be vibrations based. However, vibration monitoring cannot provide all of the information that will be required for a successful condition based maintenance program. This technique is limited to monitoring the mechanical condition and not other critical parameters required for maintaining reliability and efficiency of machinery. Therefore, a comprehensive condition based maintenance program must include other monitoring and diagnostic techniques. These techniques include

- Vibration monitoring.
- Acoustic analysis.
- Motor current analysis technique.
- Motor operated valve testing.
- Thermography.
- Tribology.
- Process parameter monitoring.
- Visual inspections.
- Other nondestructive testing techniques.

In this report, the use of vibrations analysis technique in condition based maintenance is the main area of focus because it is the most wide and reliably used technique in the industry today as described by (Mobley, 2002)
2.3 Vibrations Monitoring Technique

Due to its wide use, vibrations analysis technique has become synonymous with condition based maintenance. This technique relies on the instrumentation right from the outset. The other very simple logic behind this technique being so popular in condition monitoring in today’s times is

“All mechanical equipment in motion generates a vibration profile, or signature, that reflects its operating condition. This is true regardless of speed or whether the mode of operation is rotation, reciprocation, or linear motion. Vibration analysis is applicable to all mechanical equipment, although a common yet invalid assumption is that it is limited to simple rotating machinery with running speeds above 600 revolutions per minute (rpm).” (Mobley, 2002)

Use of vibrations analysis technique, however, is not restricted to condition monitoring; it can also be used for diagnostic purposes too. In fact it can be regarded as a primary diagnostic tool for most systems that are used to manufacture or assemble products. The reliability and performance of the plant can be enhanced by performing a variety of non-destructive testing which utilizes vibrations analysis technique.

![Figure 4: Applications of Vibrations Analysis](image)
Theory of Vibrations

Vibrations in the context of condition monitoring is defined as "a periodic motion or one that repeats itself after a certain interval of time" by Mobley R Kieth in his book 'Vibration Fundamentals' (Mobley, Vibration Fundamentals, 1999)

Following is the equation which is called as Harmonic motion describes a relation between the Vibration displacement in a spectrum with amplitude, frequency and time.

\[ X = X_0 \sin(\gamma t) \]

Where

- \( X \) = Vibration displacement (mm)
- \( X_0 \) = Maximum displacement or amplitude (mm)
- \( \gamma \) = Circular frequency (radians per second)
- \( t \) = Time (seconds)

The period of the vibration is the time interval, T. A spectrum or profile of a vibration is shown in the following figure, which shows the period, T, and the maximum displacement or amplitude, \( X_0 \)
Frequency of vibration is defined as the reciprocal of time period $T$ which can be expressed in units of rotations per minute (rpm) or cycles per second (cps) or Hertz (Hz). Such vibration oscillations can be illustrated and studied by looking at a graph of simple harmonic motion (periodic motion) of a pendulum which is illustrated in the figure.

The displacement, velocity and acceleration can be obtained by first, second and third order differentiation of the equation, respectively. (Mobley, Vibration Fundamentals, 1999)
Vibration Profiles

The process of vibration analysis in real time is interpreting the complex data obtained from a specific machine or system. In most cases the vibration spectrum obtained from a machine or a system is lot more complex than the one shown in above figures and contains other unnecessary information which must be headed off cleverly to get more lucid data. This is because of the presence of numerous sources of vibration. Each source generates a particular curve and subsequently all of them are integrated to form one complex spectrum. These profiles can be demonstrated in two formats, time domain and frequency domain. (Mobley, Vibration Fundamentals, 1999)

Time Domain

In the time domain format the vibrations data is plotted as amplitude versus time. Examples of basic formats are shown in previous figures and example for a real time industrial system is shown in following figure.

Time domain formats are usually used for reciprocating and linear movement machineries. They are also useful in overall evaluation and analysis of a system to study subtle changes in operations. On the flip side, to interpret the data from time domain efficiently, is quite a tedious task. The vibrations data in time domain format is complexly integrated. It represents the mixed spectrum of all the sources of the system at a particular instant of time. Hence, it is very difficult to find out the specific spectrum of a particular source.

![Time Domain Spectrum](image)

*Figure 6: Typical time domain spectrum of machinery equipment (Mobley, Vibration Fundamentals, 1999)*

The time-domain vibration profile was defined as a mathematical sum of simple harmonic motions by French physicist Jean-Baptiste Joseph Fourier. Fourier proposed the theory that a complex vibration spectrum is a discrete harmonic function which is a sum of simple harmonic motions.
The time domain data is regularly acquired during the life of the machine and is consistently compared with the historical data obtained at the same fundamental frequencies. However, there are significant variations in practical plant operations which can vary over the period of time. This complicates the whole idea as it is almost impossible to compare the acquired data with the historical data in such format. (Mobley, Vibration Fundamentals, 1999)

**Frequency Domain**

A frequency domain format of vibration profile is a combination of frequencies related to circular rotations or linear movements of parts of machines. Hence these vibration profiles can be considered as a multiple of fundamental frequencies of the parts, equipment or the system. Such frequencies can be expressed in terms (their units are) revolutions per minute (RPM) or cycles per minute (CPM) or cycles per second (Hertz). To analyze the operation condition of the machine in frequency domain, these fundamental frequencies must be determined first.

A time domain format can be converted to frequency domain data by using mathematical transform technique called as ‘(Fast) Fourier Transform’ which is named after Jean Fourier. FFT or advanced methods of it allows vibrations analyst to see discrete frequency peaks of vibrating components clearly. A frequency-domain plot is either displacement or velocity or acceleration versus time, unlike amplitude versus time in time domain format.

![Frequency Domain Vibration Signature](image)

*Figure 7: Frequency domain vibration signature (Barkov)*

An example of a frequency domain chart is shown in above figure.

The frequency domain spectrum is widely used where a system has a subsystem or equipments are having different fundamental frequencies. The abscissa of the frequency domain plot may be normalized to the running speed and a change in a speed will not affect the plot. A vibration which has a particular fundamental frequency will still be found in the same location on the plot for different running speed after the normalization, although the amplitude may vary. (Mobley, Vibration Fundamentals, 1999)
3. CASE STUDIES

In order to come up with state of the art in vibrations analysis technique, it is necessary to do the ground work, evaluate the current trends and get abreast of latest tools, techniques and methodologies adopted both in research and market. Hence the case studies are taken up as a research tool in the present thesis for reviewing the current trends of vibration based monitoring in industry. This part of the research can be termed as ‘retrospection’ of previous cases which are closely relevant with the thesis and can be included in the study. A look at qualitative and quantitative evidences of the historical records in same area of specialization will greatly help to organize a pathway for empirical research.

Selection of Cases

The selection of the case studies of this report is mainly based on how rich the information content of the case is and in what ways it can be of assistance for the current research. The cases represented in this report will be classified in two types in accordance with their role in the adopted research strategy

Key cases – providing the stereotypical information on Vibrations analysis technique

Outlier cases – providing atypical information on Vibrations analysis technique

3.1 Key Cases

In the present context of the thesis work, the key cases are the ones that will provide solid information for both the subject of concern and the research methodology adopted. Reviewing these case studies, will greatly help to form a base to carry out project in more planned and controlled manner and gaining in-depth knowledge about the current trends and tools used both in research and practice.

3.1.1 Key Case I

A brief review on how the maintenance performed on cryogenic pumps, using vibrations analysis technique and later on, verifying the result obtained with current signature analysis will be done. An experiment has been performed on such cryogenic pumps at the School of Mechanical and Aerospace Engineering, Institute of Marine Industry, Gyeongsang national University, Gyeongam, korea (Choi, Kim, Gu, Kim, & Jeong, 2008)

Cryogenic pumps

- A typical High Pressure Cryogenic Pump is used for transporting highly compressed Liquefied Natural Gas (LNG) to high pressure vaporization facilities
- The send-out amount in LNG receiving terminal is determined by the number of cryogenic pumps
- Hence they are considered very vital equipments and must be subjected to reliable maintenance
• Predictive or Condition Based maintenance is carried on these pumps by analyzing their vibration patterns and confirming the results obtained with current signature analysis technique
• Motor rotor bar problems are estimated by detection of electrical faults with Vibration Analysis Technique and confirmed by current signature analysis technique
• High reliability due to the combination of two techniques (Choi, Kim, Gu, Kim, & Jeong, 2008)

Process Overview

• Liquefying the Natural Gas makes storage and transportation easier
• LNG is imported and stored in ground storage tanks
• Cryogenic pumps that are installed in storage tanks, supply the LNG to secondary pumps with 8 bars, which evaporates the LNG and for exporting purpose
• The pressure is boosted up with the secondary pumps
• The more the number of cryogenic pumps, the more volume of LNG sent out
• Super cool temperature maintained, i.e. around -162°C. (Choi, Kim, Gu, Kim, & Jeong, 2008)

Challenges

• As the pumps are submerged type, it is challenging to detect faults at early stages
• Due to high operating speed and insufficient lubrication, failure occurs rapidly.
• Less time to perform Prognosis before the pump fails.
• Due to material property variation of cryogenic pumps at super low temperature, there are some restrictions to the diagnosis of pump faults (Choi, Kim, Gu, Kim, & Jeong, 2008)

Mechanical Design of Cryogenic Pump

• Cryogenic pumps are provided with a suction vessel and mounted with vessel top plate
• To support entire dynamic load of integrated shaft pump and motor, two ball bearings are installed
• Motor is cooled and bearings are lubricated by preset amount of LNG
  [Refer Figure 8]
Thrust Equalizing Mechanism is applied to control axial loads on anti-friction bearings.

Adjusting automatically inducing pressure in upper chamber, sufficient to trigger upward thrust (Choi, Kim, Gu, Kim, & Jeong, 2008)
Ratings

Pump specifications

- Capacity of the pump, \( Q = 241.8 \text{ m}^3/\text{h} \)
- Pressure, \( P = 88.7 \text{ kg/cm}^2 \)
- Head = 1439 m
- Number of impellers = 9EA
- Bearing type = ball bearings
- Number of Vanes = 6
- Rotational speed = 3580 rpm

Motor specifications

- Motor Rating = 746 kW
- Voltage = 6600 volts
- Number of poles = 2
- Current = 84.5 A
- Number of Rotor bars = 41

Vibration Spectrum Analysis

- Two types of Vibration Analysis Technique used
  1. Online Monitoring System, takes vibration signals from radial direction accelerometers installed on pump housing, as shown in the figure
     - Alarm level -10 to 15 mm/s (approximately)
     - Trip level - above 15 mm/s
  2. Portable Vibration Measurement Equipment
     - Alarm level -1.8 to 4.5 mm/s (approximately)
     - Trip level - above 4.5 mm/s

- After periodic over-haul maintenance, an increase in overall vibration amplitude was generated near top plate
- A frequency band spectrum at the top of the plate of pump–motor system obtained via portable vibration measuring system is shown in following figure
- Accelerometer oriented at radial side and roughly 1X frequency peak noted [3572.6 rpm]
- The true zooming of the above spectrum was done to study the spectrum further
• In the true zooming spectrum, multi side bands were detected around 1X and the internal frequency difference between 1X and side bands was about 0.5 Hz
• These sidebands around 1X suggest that there is a presence of certain 'pole pass frequency'
• Pole pass frequency
  \[ f_p = \text{number of poles} \times f_{\text{slip}} \]
  \[ f_{\text{slip}} = f_{\text{line}} - f_{\text{shaft}} = 60 \div 59.75 = 0.25 \]
  \[ f_p = p \times f_{\text{slip}} = 2 \times 0.25 = 0.5 \]
• Mostly the pole pass frequency sidebands (+) \( f_p \) is related to broken rotor bars or end rings
• Loose rotor bars give rise to frequencies near 'Rotor bar Pass Frequency'
  \[ \text{RBPF} = 41 \times 59.75 = 2450 \text{ hz} \]
  \[ = 147000 \text{ rpm} \]
• The following vibration spectrum for studying RBPF frequencies is obtained using online monitoring system

![Vibrations Response RBPF](Choi, Kim, Gu, Kim, & Jeong, 2008)

• Sidebands of +7200 rpm are noticed on either side of 1X, 2X and 3X RBPF in the spectrum
• Motor rotor bar problem is suspected to a large extent
• Due to the presence of resonance, unbalance and other unknown mechanical influences and conditions, it is challenging to find the severity of fault.
• These results are validated with current signature analysis (Choi, Kim, Gu, Kim, & Jeong, 2008)

**Current Signature Analysis**

• Clamp current transformers onto secondary circuit for motor
• The presence of defective rotor bar will cause motor torque to be reduced slightly, every time a pole of rotating magnet field passes by
- Presence of side bands around line frequency
- Motor torque reduction >> fractures in rotor bars
- Line frequency with two side bands

\[ f_{sync} = 2 \times f_{line} / P = 60 \text{ Hz} \]  
\[ S = \frac{f_{side}}{f_{sync}} \times \frac{P \times f_{side}}{2 \times f_{line}} = \frac{0.25}{60} \times 0.004167 \]

**After Repair**

- Vibrations were logged after repair and comparison with previous fault spectrum was done

*Figure 13: ROTOR CRACK (Choi, Kim, Gu, Kim, & Jeong, 2008)*

*Figure 14: REPLACED STATE (Choi, Kim, Gu, Kim, & Jeong, 2008)*
Figure 15: Vibration Spectrum Of Low Frequency band after repair (Choi, Kim, Gu, Kim, & Jeong, 2008)

- Vibrations reduced after repair.
- Amplitude peak of rotating frequency component (1X) was significantly reduced about 1.5 mm, approximately 80% reduction.
- RBPF side bands components almost disappeared in zooming spectrum
- Amplitude of 1X, significantly reduced.
- Spectrum completely free of any current component around line frequency 60 Hz and range (59.5 ÷ 60 Hz).

Inferences

- Vibration analysis was performed and side bands detected around 1X which is a sign of Electrical defects.
- Zoomed-In spectra showed the presence of pole pass frequency and presence of side bands at multiple harmonics of RBPF confirming rotor bar problem
- Another reliable condition monitoring technique used to validate this result and quality assurance of the experiment (Choi, Kim, Gu, Kim, & Jeong, 2008)

3.1.2 Key Case II

A detailed review of the first case leads to the inference that rotating equipment in machinery is quite a vital component. These rotating components are often subject to variable speeds. Hence the reliability of the operation must be ensured.

An experiment has been carried out on rotating equipment with different speeds under two loading conditions, during 13th International conference on Aerospace Sciences and Aviation Technology, ASAT-13, May 26 ÷ 28, 2009 at Military technological college, Cairo, Egypt by M.Kotb Ali, M.F.H Youssef, M.A Hamaad and Alaa A. El-Butch. Intentional faults were stimulated to dynamometer testing machine and the respective Fast Fourier Transform plot recorded for each case. Results shown that vibrations amplitude also vary with change in speed and load. Therefore it is not only important to choose the measuring points correctly, but also choose appropriate speed and load to perform the experiment. (Ali, Youssef, Hammad, Alaa, & Butch, 2009)
Experimental Setup

- A Dynamometer is coupled to an electric motor as shown in the figure.
- The setup is mounted on a base equipped with quick release fasteners and aligned pins ensuring the alignment.
- The specifications of the dynamometer are 250 Rating, 3000 rpm nominal speed and 220 v supply.
- Vibrations measuring device ̃ accelerometer. The measurements taken at three different positions, horizontal, vertical and axial.
- The different speeds were 1800, 2400 and 3000 rpm (30, 40, 50 Hz).
- The different faults introduced are imbalance, looseness and misalignment.

Results of the Experiment

For no load and no fault

- During the normal operation at no load and no fault conditions, vibrations data logged for three different speeds 1800, 2400 and 3000 rpm and at three different accelerometer positions, i.e. horizontal, vertical, and axial.
- The harmonics seen in the FFT plot at 1X, 2X and 3X were well below the tolerance levels according to German standard VDI 2056. (Ali, Youssef, Hammad, Alaa, & Butch, 2009)
- For the present work, vibrations signature data at fault conditions will be more of interest.
For Unbalance with no load

Figure 17: Induced Unbalance (Ali, Youssef, Hammad, Alaa, & Butch, 2009)

<table>
<thead>
<tr>
<th>Sensor Position</th>
<th>Load</th>
<th>No Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1×</td>
<td>2×</td>
</tr>
<tr>
<td>Speed</td>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>30 Hz</td>
<td>5.42</td>
<td>0.20</td>
</tr>
<tr>
<td>40 Hz</td>
<td>4.56</td>
<td></td>
</tr>
<tr>
<td>50 Hz</td>
<td>3.89</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Table 2. Table different accelerometer positions  (Ali, Youssef, Hammad, Alaa, & Butch, 2009)

Figure 18: FFT Spectrum for Unbalance (Ali, Youssef, Hammad, Alaa, & Butch, 2009)
With the addition of extra mass of the shaft of the coupling, unbalance was been introduced.
As a result, high peaks at 1X in all the three accelerometer positions is noticed

For misalignment with same unbalance with no load

### Table 3. Vibration amplitude with misalignment (Ali, Youssef, Hammad, Alaa, & Butch, 2009)

<table>
<thead>
<tr>
<th>Speed</th>
<th>Sensor Position</th>
<th>No Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1× 2× 3× 4×</td>
<td>1× 2× 3× 4×</td>
</tr>
<tr>
<td>30 Hz</td>
<td>0.32 0.42</td>
<td>0.62 5.80</td>
</tr>
<tr>
<td>40 Hz</td>
<td>0.44 0.86</td>
<td>0.78 8.06</td>
</tr>
<tr>
<td>50 Hz</td>
<td>0.43 0.85 0.28</td>
<td>1.14 3.31</td>
</tr>
</tbody>
</table>

Intentional misalignment developed by releasing the fasteners and alignment pins
As a result a small elevation can be seen to the peak already present due to unbalance in all three accelerometer directions
Also high amplitudes are observed at 30 and 40 Hz for vertical accelerometer position

Effect of Looseness with 0.5 Nm load

![Figure 19: FFT for vertical Looseness at 40 Hz with 0.5 Nm load (Ali, Youssef, Hammad, Alaa, & Butch, 2009)](image-url)
Table 4. Vibration amplitude with looseness at 0.5 Nm load (Ali, Youssef, Hammad, Alaa, & Butch, 2009)

<table>
<thead>
<tr>
<th>Load Speed</th>
<th>Horizontal</th>
<th>Vertical</th>
<th>Axial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Position</td>
<td>1&lt;sup&gt;x&lt;/sup&gt;</td>
<td>2&lt;sup&gt;x&lt;/sup&gt;</td>
<td>3&lt;sup&gt;x&lt;/sup&gt;</td>
</tr>
<tr>
<td>30 Hz</td>
<td>0.45 0.25</td>
<td>0.39 0.81 1.51</td>
<td>0.26 0.39 0.41</td>
</tr>
<tr>
<td>40 Hz</td>
<td>0.31 0.31</td>
<td>0.54 0.90 3.18</td>
<td>0.47 1.38</td>
</tr>
<tr>
<td>50 Hz</td>
<td>0.36 0.11 0.68</td>
<td>1.39 1.10 0.23</td>
<td>0.65 0.62 0.25</td>
</tr>
</tbody>
</table>

- By loosening the fixing bolts of dynamometer, looseness fault is introduced to the systems and measurements are logged and tabulated.
- Increase in the vibration amplitude for 2X in the vertical direction of accelerometer at 40 and 50 Hz speeds.
- High vibration amplitude at 1X and 3X in the axial position at 50 Hz speed.

**Inferences**

1. A high vibration amplitude of 1X in all three directions for IMBALANCE and the amplitude increases with speed surpassing permissible limit.
2. The 1X amplitude caused by unbalance is further incremented due to misalignment, but only in vertical position.
3. The effect of applying looseness and load is that the amplitude at 2X is increased in vertical position.
4. The experiment suggest that for carrying out a reliable experiment in CBM measurements must be taken in same positions and under same operating conditions (Ali, Youssef, Hammad, Alaa, & Butch, 2009).

**3.2 Relevant Cases**

In order to study further about vibration signature analysis and their consonance with different types of faults and their stages, relevant cases will also be reviewed apart from the key cases evaluated above. Unlike the key cases, these relevant cases will provide knowledge with indirect relevance. This will augment the thesis work with more broad and comprehensive explanation in the current research methodology.

**3.2.1 Relevant Case I**

At the Air Force Institute of Technology, proactive maintenance using vibrations analysis technique was performed on a military aerial ship after the air incidents to find out the causes for notable damages. The experiment was performed by at the Division for Aero-engines, Warsaw. The tests were performed on the propelled engine of the jet, which was selected as a point of reference for the prognosis process of the system as a whole.
**Description of the object**

![Diagram of the object](image)

*Figure 20: System Model (SPYCHAŁA, SZCZEKALA, & ŻOKOWSKI, 2009)*

- Roller Bearings are crucial elements to ensure the reliability and safety in engines
- The most frequent occurring fault is the damage of the rolling bearing at the central support
- Impulses of the damped vibration with frequency of the turn of the shaft of the jet propelled engine are generated by the damaged bearings. In the present scenario, the range is 6900 rpm to 15,600 rpm (115-260 Hz)
- Fundamental fault frequencies of the bearings are determined to calculate inner race faults, outer race faults and bearing separations
- The accelerometers used are piezo-electric sensors and the vibrations signature logged via these sensors are analyzed in the sampling frequency 10000 Hz in *LabView* software. (SPYCHAŁA, SZCZEKALA, & ŻOKOWSKI, 2009)

**Diagnosis for bearing element fault**

After performing the FFT on time domain spectrum, the following plot is obtained

![FFT plot](image)

*Figure 21: Frequency domain spectrum for bearing element* (SPYCHAŁA, SZCZEKALA, & ŻOKOWSKI, 2009)
Inference

It can be observed from the spectrum above that the presence of sub harmonics at half the fundamental frequency, along with a peak at 1X and their multiples could mean backlash in the case of bearing or may be instability of bearing or its brackets. (SPYCHAGA, SZCZEKALA, & ŁOKOWSKI, 2009)

3.2.2 Relevant Case II

In this research paper CBM via vibrations analysis technique is performed on induction motor which is described as which is described as Òversatile prime mover in the present day industry because of its good self-starting capability, simple and rugged structure, low cost, and reliabilityÓ (Khwaja, Gupta, & Kumar, 2010) Sin et al. Suggests that 40% of the faults in induction motor are bearing faults and out of those 18% are outer race and 64% are inner race faults

Experimental setup

The experiment is performed on 3 types of NBC 6308 bearings that are having inner race faults and outer race faults. Vibration signatures are recorded with PU/601R, analog signal into a machine analyzer. Sampling frequency is 2560 Hz. The system is interface with the PC using a data acquisition DAQ card for digitizing purpose. The analysis is done in ØLabViewØ software. (Khwaja, Gupta, & Kumar, 2010)

Diagnosis in frequency domain

Following are the fundamental frequencies of the bearing for diagnostic purposes

For outer race fault

\[ f_o(\text{Hz}) = (N/2)f_r[1 - b \cos(\beta)/d] \]

For inner race fault

\[ f_i(\text{Hz}) = (N/2)f_r[1 + b \cos(\beta)/d] \]

For ball defect

\[ f_{bd}(\text{Hz}) = df_r/b \ [1 + b \cos(\beta)/d]^2 \]

For cage defect

\[ f_{cd}(\text{Hz}) = f_r/2 \ [1 - b \cos(\beta)/d] \]
Where

\[ f_r = 24 \text{ Hz} \] is the rotational frequency

\[ N = 7 \] is the number of balls

\[ b = 15.081 \text{ mm}, \text{ ball diameter} \]

\[ d = 65 \text{ mm}, \text{ bearing pitch diameter} \]

\[ \hat{\theta} = 0 \] is the contact angle of the ball (with the races)

\[ f_O, f_I, f_{bd}, \text{ and } f_{td} \] are the characteristic vibration frequencies which are 64.62 Hz for outer race, for inner race 103.38 Hz, for ball defect 49.23 Hz, and for train defect 9.23 Hz for bearing

*Figure 22: Frequency plot when outer race fault is introduced (Khwaja, Gupta, & Kumar, 2010)*
Figure 23: Frequency plot when inner race fault is introduced (Khwaja, Gupta, & Kumar, 2010)

Where $A$ is rotational frequency, $B$ is ball spin frequency, $C$ is outer race fault frequency and $D$ is inner race fault frequency.

**Inferences**

- When outer race fault is introduced in the bearing a sharp peak at 1X is noticed and more peaks at 3X, 5X and 7X are noticed.
- When inner race fault is introduced in the bearing a sharp peak at 1X is noticed.

(Khwaja, Gupta, & Kumar, 2010)
4. Technical Evaluation

CNC Machine

CNC milling machines are also known as machining centers is a powered mechanical device which are commonly used to machine solid materials. They are classified into two types basically, horizontal and vertical. The 'horizontal' and 'vertical' positions refer to the orientation of the main spindle. The sizes of the CNC machines ranges from small, bench mounted systems to large room-sized machine. The difference between a drill and a mill machine is that the workpiece is stationary during the drilling operation, while it moves in radial direction against the tool in milling process.

In the CNC machines, an extra degree of freedom is provided in Z-direction. The 'Computerized Numerical Control' (CNC) refers to the advanced automation of the machines tools where end to end designs are developed using a combination of 'Computer Aided Design' and 'Computer Aided Manufacturing' in an encoded program. A computer file is produced by the program that is interpreted to extract the commands needed to operate a particular machine via a postprocessor, and then loaded into the CNC machines for production. (Milling Machine, 2011)

4.1 Mazak 3 axial milling machine

The experiment is carried out on Mazak 3 axis milling machine at the department of industrial production, Royal Institute of technology, Sweden. The subject 3 axis Mazak milling machine is very similar to a conventional milling which has the degree of freedom of tool in three axis, i.e. X.Y.Z (Left and right, forward and backwards, up and down). However, the angle of the head is static or cannot be moved in anything but the up and down (Z axis) direction automatically. In this machine, all conventional milling processes such as end milling, slot milling, face milling, drilling, tapping, trepanning, chamfering and 3D contour milling is also possible.

The Mazak 3 axis CNC milling machine (subject) is also available with tool changers and pallet changers for high volume productions. The variety of cutting tools that can be used with this machine are end mills, slot mills, bull nose cutters, ball nose cutters, drills, taps, thread milling cutters, boring heads, reamers, slitting saws, tee slot cutters, dovetail cutters, and even laser marking heads to perform a large variety of machining operations.
Figure 24: Mazak 3 axis milling machine

Figure 25: Parts layout – construction and operation
Lubrication schedule

<table>
<thead>
<tr>
<th>S.No</th>
<th>Lubrication point</th>
<th>Quantity</th>
<th>Recommended oil</th>
<th>Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydraulic power unit</td>
<td>63 ltrs</td>
<td>P.T.E 24</td>
<td>Change oil and clean filter every six months</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tellus Oil 32</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>UniPower SQ 32</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Slide path ball screw transmission</td>
<td>3 ltrs</td>
<td>VACTRA 2</td>
<td>If necessary do oil changes annually</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>FEBIS K68</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TONNA OIL T68</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Lubrication of spindle head</td>
<td>25 ltrs</td>
<td>D.T.E 21</td>
<td>Change oil and clean filter every six months</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tellus Oil c10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SPINESSO 10</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Lubrication Schedule for preventive maintenance

Operations

Formal training and hands on knowledge is required for operating a CNC milling machine. For every specific operation the operator must put information into the machine’s computer control.

This program containing instructions (information) also include the tooling location and the dimensions that will be required for operations on work piece. Every operation during the first machine cycle must be monitored to make sure that none of the tools break so as to avoid damage to the machine or the expensive work pieces.

Instructions for operating 3 axis CNC mill machine

1. The machine is set to zero so that it can use the dimensions in the program in absolute plane to operate on work piece accurately and also the reference point can be set. The machine is toggled to manual mode by pressing the positive X-axis traverse button for a second and then by pressing the Y-axis button and consequently Z-axis button. The reference point will be set to home position

2. A vise or work piece is placed on holding device on the table. A dial indicator is also placed on the spindle and moved above the vise manually. The tip of the dial indicator is placed on the front jaw and the dial indicator is moved along the X-axis manually. When the indicator does not move, the vise is straight and then the dial indicator can be removed and the spindle is set back to the home position.
3. The availability of all needed tools is ensured in the tool turret. The machine is set in 'tool-teach' mode and each tool is individually called for. The 'tool-teach' mode can usually be found on the tool information screen. The machine will fetch each tool to the probe and when the tool is taught a beep sound occurs.

4. The tool is set such that it is just above the work piece touching the surface top and the zero point is set for Z axis, so that any depth cuts can be calculated easily, which is the most crucial dimension in milling operation.

5. An edge finder is placed in the spindle and set to 1,000 revolutions per minute, or rpm such that its tip is very close to the right side of the material. Eventually, the edge finder is brought closer to the material. That is the edge of the X-axis, which set to zero to the reference point. The same directions are followed on the Y-axis and the point is set as Y zero.

6. The spindle is set to home position and program is started. Rapids are set to very low. Rapids determine the speed of the spindle during tool changes and the orientations it take for cutting. Adjustments to the rapids can also be made with the override on the face of the control and set them anywhere between 0 and 100, which is full speed. The first piece closely watched for any mistakes or errors in the setup and to make sure it is coming in correct direction [CNC concepts Inc]

4.2 Fault possibilities in MAZAK machine

Imbalance

The 3 axis mill machine has basic components shown in the above figure such as spindle shaft, motor shaft, rolling elements bearings etc which are the prime area of concern. If the balance is perfect all rotating equipment turn on their center line. On the other hand, this is not the case in industrial machine like the subject MAZAK mill machine in the present case. Imbalance of in different rotating and linear equipment is one of the most common types of faults. This is caused when more weight is shift on either side of the centerline of a rotor.

Diagnosing Imbalance is very crucial as it will put undue stress on bearings and seals. If imbalance is controlled and rectified, secondary damages to the machine can also be avoided. As the subject machine is high speed machine, the precision balancing is even more important. The spindle shaft and motor shaft in the mill machine may have static imbalance (imbalance when the spindle is static) or coupling imbalance (Imbalance caused when the spindle starts rotating due to centrifugal forces). In both case, a high peak of 1X can be noticed and if the machine is free from other faults, this 1X peak will dominate the spectrum.
**Misalignment**

**Misalignment** in the MAZAK mill machine may be caused when the centerlines of coupled spindle shaft and motor shaft do not coincide. If the centerlines are parallel but not coincident then it can be termed as 'Offset misalignment' else angular misalignment. Angular misalignment can be diagnosed if the spectrum has high 1X peaks followed by reasonably high peaks at 2X and in some cases even at 3X. In case of parallel vibrations, the 2X peak mill most probably be higher than 1X peak

Alike Imbalance, even the misalignment leads to the secondary faults in a machine like the subject machine. Therefore it can also be termed as one of the important faults that has high priority for diagnosis

**Rolling element bearing**

Rolling element bearing fault is another type of fault which has significant impact on machine life. Statistics from 'I learn vibration' course show that less than 10% of the bearing run for their desired lifetime. About 40% of the bearing faults are due to improper lubrication and 30% are from improper mounting. The machine would become very reliable if the bearing faults can be avoided, which unfortunately is not the case.

Bearing element faults are usually detected if the vibration spectrum has non-synchronous or sub synchronous (peaks at ½ X or 3/2 X). To analyze the spectrum, four types of frequencies related to bearings are calculated, ball pass inner race (BPI), Ball pass outer race (BPO), cage rate (FT) and ball spin BS

Defect on inner race (BPI) = ½ n (1+d/D cos \( \theta \))

Defect on outer race (BPO) = ½ n (1-d/D cos \( \theta \))

Defect on cage (FT) = ½ (1-d/D cos \( \theta \))

Defect on ball (BS) = ½ D/d [1-(d/D)^2 cos^2 \( \theta \)]

Where,

d = Ball diameter

D = Pitch diameter

N = Number of balls

\( \theta \) = Contact angle
4.3 Experimental Setup

The experiment is carried at department of production engineering, royal institute of technology. The steps to be followed to ensure the reliability of the experiment are

1. Proper selection of transducer (Displacement, velocity or acceleration sensor)
2. Properly mounting the sensor on Mazak machine
3. Collection of the data

Transducers

There are three types of transducers that can be selected for the measurements. They are displacement, velocity and acceleration measuring sensors respectively. In the present research work accelerometer is chosen as it is most suitable for measurements in high speed machines such as MAZAK 3 axis mill machine.

Accelerometer

An accelerometer, makes use of piezoelectric (i.e., pressure-sensitive) films to convert mechanical energy into electrical signals. The weight of the device is generally suspended between two piezoelectric films. When vibrations are sensed, the weight moves in response and contracts the films, which generate an electrical signal for every contraction.

The accelerometer used for the experiment is calibrated in compliance with ISO 10012-1 and former MIL-STD-45662A and traceable to NIST. The specifications are

Voltage sensitivity = 96.0 mV/g
Transverse Sensitivity = 2.4 %
Resonant frequency = 27.5 KHz
Output bias level = 9.1 V
Time constant = 1.1 s
Range = 50 ± g
Resolution = 0.001 g
Temp Range = -20 ± F

*Figure 27: Power source for accelerometer*

**Cabling**

The accuracy and reliability of a measurement system also depends on reliability of cabling system. Capacitive loading of long cables may be used for higher frequency signals:

\[
F_{\text{max}} = \frac{10^9}{2 \pi CV(I-1)}
\]

Where,

- \( F_{\text{max}} \) = Maximum frequency (Hz)
- \( C \) = Cable capacitance (pF)
- \( V \) = Peak voltage output from sensor (V)
- \( I_c \) = Constant current available from power source (mA)
- 10 = Scaling constant
- \( p = 3.14159 \)
Mounting / installing the accelerometer

In order to achieve good and reliable results correct installation is of paramount importance. The probes used for the data transfer are called 'eddy current probes' which are calibrated according to standards. Permanent stud mounting is provided near the spindle shaft of Mazak machine which insures the safe location of accelerometer as well as fine data transmission across the system without any probability of interruption. As the measurements are to be taken in horizontal, vertical and axial directions a tri-axial accelerometer is used.

Collection of data

The data collection is done in the following way:

- Condition the signal from accelerometer using an 'anti-aliasing filter'
- Digitize the signal using an 'A/D converter'
- Produce the spectrum in the computer and store it as 'Matlab' files

Aliasing

Aliasing can be described as the effect that causes different signals to become identical (aliases of one another) when sampled. It can also refer to the misrepresentation that results when signal interpolated from samples is different from original continuous signal.

Figure 28: Anti Aliasing filter

Hence 'anti aliasing' filters are used to select the frequency of sampling (which is more than double the Nyquist frequency) to avoid aliasing of the signals and the data becomes very clear and ready for analysis purpose.
Digitizers

An Analog to digital converter is used to digitize the data as the data collector will understand the information in digital format which is in discrete time format. The 'sampling rate' has to be defined before the measurements are begun. The features that are to be kept in mind while selecting an A/D converter are resolution, quantization error, non linearity, aperture error and accuracy.

*Figure 29: Analog to Digital converter*
5. ANALYSIS

With efficient experimental setup and data acquisition the vibration signature must be comprehensible to obtain results. This can be done by converting time domain data to frequency domain data using 'Fast Fourier Transform'. This frequency domain spectrum can be further used to detect, isolate and verify incipient problems providing in-depth analysis and scope for prognosis using root cause analysis.

The two types of analysis usually employed are trending analysis and water fall analysis. By analyzing the continuous trends of the spectra the faults can be detected in early stages and shaping action plans to rectify them. The signatures are collected on regular basis so that the trending can be compared to understand the behavior of the machine. Trending analysis is based on 'narrow band' or 'broad band', while a graphical comparison of the relative change of the mill machine's full vibration signature and its discrete frequency components over a certain period of time.

5.1 Alarm limits

After the data is acquired, setting the alarm limits poses quite a challenge. The reference level has to be decided and the boundary conditions for acceptable, moderate and extreme level must be set. The reference level is set considering the size of the machine, load during the operations and the history of the machine. In the present case fixed alarm limits are considered according to standards rather than reading the vibration and calculating alarm limit on instinct. The ISO standard used is 2372/10816 which provides the acceptance guidance for the machines with speeds ranging 600-12000 rpm)

![Figure 30: ISO 80186 standard (ISO standard 10816)](image)

<table>
<thead>
<tr>
<th>Vibration Velocity (IPS)</th>
<th>Group 4 Integrated Driver</th>
<th>Group 3 External Driver</th>
<th>Group 2 Motors 160 ≤ H ≤ 315 mm</th>
<th>Group 1 Motors H &gt; 315 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rigid</td>
<td>Flexible</td>
<td>Rigid</td>
<td>Flexible</td>
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<tr>
<td>0.71</td>
<td></td>
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<tr>
<td>0.43</td>
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<td>0.28</td>
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<td>0.18</td>
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<tr>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.2 Power Spectrum Density

Power spectral density function (PSD) shows the strength of the variations in a function of frequency. PSD is incorporated in present analysis to see at which frequencies variations are strong and at which frequencies variations are weak. The unit of PSD is energy per frequency (width) and you can obtain energy within a specific frequency range by integrating PSD within that frequency range. Computation of PSD is done in matlab program for the present project.

The PSD matlab program developed for the current case:

```matlab
Fs=1200000; %Fs=1000 Hz
Signallength=length(Zmovementuppexp2(:,1)); %N=1000;
dt=1/Fs;
t=dt*(0:Signallength-1);
y=Zmovementuppexp2(:,1);
fig1=figure();
plot(t,y);
title('the signal in time');
WindowSize=256;
NumberofTimesToRepeat=Signallength/WindowSize;
w=window(@hann,WindowSize);
win=repmat(w,NumberofTimesToRepeat,1);
y=win.*y;
nfft=1000000;
Y=fft(y,nfft);
Y(1)=[];
Pyy=Y.*conj(Y)/nfft;
f=Fs/nfft*(0:nfft/2+1);
plot(f,Pyy(1:nfft/2+2)); title('power spectral density');xlabel('Frequency (Hz)');
```
6. RESULTS AND DISCUSSIONS

The answers for the research question will be provided in this chapter. An assessment is also made as how the thesis has contributed to the theory of vibrations analysis technique in Condition Based Maintenance technique.

Based on the analysis and the theoretical framework provided in the earlier chapters, the experiment has been performed on the MAZAK 3 axis milling machine, and results obtained from the analysis phase will be discussed in this chapter.

Figure 31: MAZAK 3 axis mill machine - design layout
6.1 Calculation of Fundamental Frequencies

**Rotating Components in the Spindle of Mazak machine**

Angular ball bearing on the spindle Shaft

![Angular ball bearing CAD drawings](image)

**Figure 32: Angular ball bearing – CAD drawings**

Ball diameter, \( d = 10 \text{ mm} \)

Number of balls \( N = 12 \)

Pitch diameter \( D = 60 \text{ mm} \)

Contact Angle, \( \bar{\alpha} = 30 \text{ degrees} \)

Defect on inner race (BPI) = \( \frac{1}{2} n \left( 1 + \frac{d}{D} \cos \bar{\alpha} \right) = 6.86 \)

Defect on outer race (BPO) = \( \frac{1}{2} n \left( 1 - \frac{d}{D} \cos \bar{\alpha} \right) = 5.13 \)

Defect on cage (FT) = \( \frac{1}{2} \left( 1 - \frac{d}{D} \cos \bar{\alpha} \right) = 0.43 \)

Defect on ball (BS) = \( \frac{1}{2} \frac{D}{d} \left[ 1 - \left( \frac{d}{D} \right)^2 \cos^2 \bar{\alpha} \right] = 2.94 \)
Radial ball bearing on motor shaft

Figure 33: Radial ball bearings - CAD Drawings

Ball diameter, d = 7.5 mm
Number of balls N = 24
Pitch diameter D = 90 mm
Contact Angle, \( \bar{\alpha} \) = 0 degrees

Defect on inner race (BPI) = \( \frac{1}{2} n (1 + d/D \cos \bar{\alpha}) \) = 13
Defect on outer race (BPO) = \( \frac{1}{2} n (1 - d/D \cos \bar{\alpha}) \) = 11
Defect on cage (FT) = \( \frac{1}{2} (1 - d/D \cos \bar{\alpha}) \) = 0.46
Defect on ball (BS) = \( \frac{1}{2} D/d [1 - (d/D)^2 \cos^2 \bar{\alpha}] \) = 5.96

To calculate the fault frequencies of bearings the above indexes must be multiplied by the rotation frequencies of the shaft on which they are mounted.
**Gear frequencies**

There is one gear with 63 teeth on the motor shaft \((Z_1=63)\)

And a gear of 42 on the spindle shaft \((Z_2=42)\)

Gearing ratio=\(63/42=1.5\)

\[ \Rightarrow \text{Motor shaft fundamental frequency} = \text{Spindle shaft fundamental frequency} \times \text{gear ratio} \]

**Calculating expected frequencies based on different RPM**

<table>
<thead>
<tr>
<th>Frequencies</th>
<th>Spindle shaft</th>
<th>Motor shaft</th>
<th>Gear mesh</th>
<th>Angular Ball Bearing</th>
<th>Radial Ball Bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td></td>
<td></td>
<td></td>
<td>BPI</td>
<td>BPO</td>
</tr>
<tr>
<td>660</td>
<td>11</td>
<td>16.5</td>
<td>693</td>
<td>75</td>
<td>58</td>
</tr>
<tr>
<td>3000</td>
<td>50</td>
<td>75</td>
<td>3150</td>
<td>334</td>
<td>256</td>
</tr>
<tr>
<td>4800</td>
<td>80</td>
<td>120</td>
<td>5040</td>
<td>549</td>
<td>410</td>
</tr>
</tbody>
</table>

Table 6. Fault Frequencies

6.2 Inferences

**Inference 1**

When the spindle is moving in Y direction

![Figure 34: 18th March 2011 period gram of Y_plus (accelerometer x-axis) - 660 rpm](image)

Figure shows a low peak in spindle fundamental frequency (11 HZ) and a high peak in motor shaft (16.5 HZ) and also peaks at twice these frequencies and sidebands. Based on rule base
attached to this report a high peaks in 1X of motor shaft and sidebands of twice 2x (16.5, 33, 49.5) can be a sign of failure modes of **Eccentricity of Rotor and stator**. Peaks in 2X of motor shaft can show winding failures in motor but as it is shown in figure 1 there is a low peak in 33 Hz.

**Inference 2**

![Periodogram/abs²](image)

*Figure 35: 21st March 2011 period gram of \( Y_{plus} \) (accelerometer x-axis)- 660 rpm*

The vibration analysis of 28 of March and 4 of April includes the similar observations including 1X and 2X and harmonics of fundamental frequencies of motor shaft and spindle shaft. As an example figure 9 shows strong oscillation of twice motor shaft fundamental frequency 33 HZ which can be a sign of **Eccentricity of rotor and stator**.

**Inference 3 (Gear Mesh)**

When the spindle shaft is rotating at 660 RPM the gear mesh frequency is calculated as 690 Hz as calculated in Table 6.
Figure 36: 18<sup>th</sup> March 2011 period gram of $Y_{plus}$(accelerometer x-axis)-660 rpm

Figure 37: 18<sup>th</sup> March 2011 period gram of $Y_{plus}$(accelerometer y-axis)-660 rpm
Gear mesh frequencies are noticed in all three directions of accelerometer. There is a high probability of spilled or pitted gear.

**Inference 4 (Bearing faults)**

When the spindle shaft speed is set to 660 rpm, i.e. 11 Hz, following signature was recorded.
With the rotational speed of 660 RPM (11HZ) peaks at bearing frequencies (58,65,121,143 HZ) are not significant.

**Inference 5 (Bearing faults)**

When the spindle shaft is rotated at 3000 rpm (50 Hz), the angular ball bearing frequencies are

Angular Ball Bearings

BPI = 334 Hz

BPO = 256 Hz

Cage, FT = 21.5 Hz

Ball defect, BS = 147 Hz
Radial Ball Bearings

BPI = 650 Hz

BPO = 550 Hz

Cage, FT = 23 Hz

Ball defect, BS = 298 Hz

Angular bearings:

Expected BPI: 334hz ----- Closest: 338Hz (very low amplitude)

Expected BPO: 256hz ----- Closest: 232Hz (far)

Expected Cage: 21.5hz ----- Closest: 24Hz (very low amplitude)

Expected BS: 147 Hz ----- Closest: 150 Hz, (could also be because of fundamental frequency multiple)

Radial Bearings

Expected BPI: 650hz ----- Closest: 651 Hz, but very low amplitude

Expected BPO: 550hz ----- Closest: 551 hz, but very low and 564 Hz (too far?)

Expected Cage: 23hz -----Closest: 24 hz but very low amplitude

Expected BS: 298 hz ---- Closest: Some disturbance at 294 Hz

**Final Word**

- Strong probability of fault in eccentricity of rotor and stator is noted.
- Gear mesh frequencies are accurate to the large extent
- However, data in relevance with ball bearings is not clear enough
7. CONCLUSIONS

The analysis of the Mazak 3 axis mill machine is done and the results are noted. The condition indicators for eccentricity in rotor and stator of the spindle shaft and gear mesh are noticed. However, signs for ball bearing problems remained ambiguous in the present research work. Extensive literature study has been done by reviewing research papers. The papers were categorized as 'Key cases' and 'outlier cases' depending upon the type of information they provided.

Also the research methodology was adopted in accordance with the project management strategies depicted in the research papers. The state of the art technique in vibrations analysis technique used for condition based maintenance methodology has been exercised with practical measurements on mill machine using data acquisition hardware/software and analysis done in Matlab. The research project still leaves a room for the 'Prognosis' part

Prognosis

It is suggested that after performing the diagnosis and assuring the quality of the results by repeatable measurements, 'Root cause analysis' be performed for identifying the cause for the damage. The cause-effect identification tools such as failure mode effect analysis and Fault tree analysis comes in very handy to identify the root of the fault. The overall reliability of the machine can be improved and availability will be assured during the operations after the prognosis part is complete.
8. APPENDIX

This contains thesis proposal formed in order to continue the work this thesis has started. The purpose is to evaluate the improvement in overall reliability and maintainability of system using a priori defined approach

Thesis Proposal

Purpose

Evaluate the possibilities of performing the prognosis based on the data provided by the documented research. The prognosis can be done by using 'root cause analysis'. To further optimize the reliability, availability, maintainability and supportability, ‘Anticipatory failure determination' can be performed, which is a design for maintainability technique implemented during design stage.

A framework can be developed to connect the concepts of Condition based maintenance and Anticipatory failure determination.

Work structure

- Develop a framework and apply to a 'subject' machine
- Perform functional analysis
- Perform AFD to identify possible failures that can upset function of the system
- Examine the 'effectiveness' in im
- Proving the performance of the system

General Information

<table>
<thead>
<tr>
<th>Technical area</th>
<th>-</th>
<th>Strategic Maintenance systems</th>
</tr>
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<tbody>
<tr>
<td>Targeted students</td>
<td>-</td>
<td>Two students with at least a Bachelor degree or equivalent</td>
</tr>
<tr>
<td>Preferred Background</td>
<td>-</td>
<td>Industrial or Mechanical or Electrical Engineering</td>
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<tr>
<td>Subject machine</td>
<td>-</td>
<td>Mechanical heavy machines or power systems</td>
</tr>
</tbody>
</table>
References


EESTI STANDARD. (den 11 08 2010). Estonia.

Federal standard 1037C. (den 07 08 1996).


*ISO standard 10816*.


