ANALYSIS OF VIBRATION CHARACTERISTICS IN CENTRIFUGAL PUMP

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed………………………………… (Brian Pravinnayagam A/L Adie Nayagam)

Date…………………………………… (13/6/2021)

STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated.

Other sources are acknowledged by giving explicit references.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BEP	Best Efficient point
BPF	Blade Passing frequency
BPF	Band Pass Filter
CBM	Condition-based monitoring
DAQ	Digital Acquisition System
DC	Direct Current
DFT	Discrete Time Fourier transform
FFT	Fast Fourier Transform
MCSA	Motor Current Signature Analysis
MFS	Machine Fault Simulator
NPSH	Net Positive Suction Head
NPSHA	Net Positive Suction Head Available
NPSHR	Net Positive Suction Head Required
RMS	Root Mean Square
RPM	Rotation Per Minute
SBs	Sidebands
VPF	Vane Passing frequency
Hz	Hertz

ANALISIS KARAKTERISTIK GEGARAN DI PAM EMPAR

ABSTRAK

Pam Empar adalah jentera berputar yang digunakan dalam pelbagai aplikasi seperti alam pertanian, petroleum, pembinaan, industri dan juga digunakan dalam kumbahan dan sisa buangan. Pam Empar yang beroperasi dengan operasi berterusan boleh mengakibatkan kegagalan operasi pam kerana beberapa kerosakan barang berlaku di pam empar yang akan memerlukan penyelenggaraan dan perkhidmatan yang mahal untuk pam empar. Karya ini bertujuan untuk menyiasat karakteristik getaran dalam pam empar yang beroperasi dengan keadaan sihat (biasa) dan dengan kesalahan mekanikal disebabkan oleh pelekap longgar dan kavitasi oleh kerana penapis yang disekat. Isyarat getaran dari pam centrifugal diperolehi dengan menggunakan accelerometer yang diletakkan di bahagian atas dan sisi pam empar untuk mengenal pasti getaran mendatar dan menegak pam. Isyarat getaran dianalisis menggunakan domain masa dan spektrum Fast Fourier Transform (FFT). Analisis time-domain menunjukkan bahawa pam yang sihat yang dikendalikan di bawah keadaan kadar aliran minimum menghasilkan amplitud getaran yang lebih tinggi daripada keadaan aliran maksimum. Tahap getaran adalah lebih tinggi pada kelajuan operasi yang tinggi. Penapis yang disekat dan pam pelekap longgar menghasilkan amplitud getaran yang lebih tinggi daripada pam yang sihat untuk kedua-dua kadar aliran minimum dan kadar aliran maksimum. Analisis spektrum Fast Fourier Transform (FFT) pantas menandakan frekuensi kesalahan yang dihasilkan oleh jenis kesalahan ini dan menunjukkan bahawa analisis FFT berguna dalam mengesan frekuensi kesalahan yang dihasilkan oleh penapis yang disekat dan pelekap longgar dan boleh digunakan untuk pengesanan kesalahan barang dalam pam empar.

ANALYSIS OF VIBRATION CHARACTERISTICS IN CENTRIFUGAL PUMP

ABSTRACT

Centrifugal pumps are rotating machinery used in various applications such as in agriculture, petroleum, construction, industry and also used in sewage and waste. Centrifugal pump operating with continuous operation may result in pump failures due to some faults in the centrifugal pump which will require expensive maintenance and service for the centrifugal pump. This work aims to investigate the vibration characteristics in centrifugal pump operating with healthy (normal) condition and with the presence of mechanical fault due to loose mounting and cavitation due to a blocked filter. Vibration signals from the centrifugal pump are obtained by using an accelerometer which was placed on the top and side of the centrifugal pump for identifying horizontal and vertical vibration of the pump. The vibration signal is analyzed using time domain and Fast Fourier Transform (FFT) spectrum. Time-domain analysis shows that the healthy pump operated under minimum flow rate condition produces higher vibration amplitude than the maximum flow condition. The vibration level is higher at a high operating speed. The blocked filter and loose mounting pump produce a higher vibration amplitude than the healthy pump for both the minimum flow rate and maximum flow rate. Fast Fourier Transform (FFT) spectrum analysis denotes the fault frequencies produced by these types of faults and shows that the FFT analysis is helpful in detecting the fault frequencies produced by the blocked filter and loose mounting and can be used for fault detection in a centrifugal pump.

CHAPTER 1

INTRODUCTION

1.0 Introduction

In the industrial era, centrifugal pumps are vital for pumping fluids such as water, oils etc. They are often used for high-pressure applications such as pumping water in dams, and they are also used in our neighborhood fire hydrant to pump water and used in our homes. They are also used in our air conditioning system and drainage system. Pumps are essential to raising or lower pressure for the use of transporting fluid by using centrifugal force.

Due to a recent survey, cavitation and mechanical faults in pumps are among the leading causes that may make a pump to break down; Mechanical faults include unbalanced rotating object, damaged impeller, looseness in a bolt and worn-out bearings. Cavitation also occurs at the suction side of the centrifugal pump. Cavitation is the development of vapour bubbles inside the fluid if static pressure falls below vapour pressure. The bubbles will eventually collapse inside the pump leading to an increasing level of vibration. Suppose cavitation or any mechanical faults is left without any treatment. In that case, it is possible for the pump to be in failure, which causes the impeller of the pump to be destroyed, having high vibration from the faulty parts in the pump which causes high power consumption. Pump blockage is one of the main reasons why cavitation occurs as is this may cause pressure difference at the pump inlet and outlet.

According to (Ahmed Al-Obaidi, 2018), the total maintenance cost for a pump is close to 70%, which is the highest maintenance cost compared to other rotating machinery. Therefore, to avoid any machinery faults in the pump, conditioning monitoring has been proposed to identify faults beforehand to avoid such disastrous events from happening. Condition monitoring is a very safe and efficient method for undergoing maintenance in a range of industries such as pump industries, milling industries, etc. Vibration analysis is a commonly used method in the condition monitoring of rotating machinery as shown in Figure 1.1. Moreover, vibration analysis is used in the centrifugal pump to identify problems. The condition of bearings, unbalance in the pump, cavitation, and mechanical looseness can easily be detected using vibration analysis.

Vibration analysis of centrifugal pump is studied by many researchers such as (Al-Obaidi, 2019b), who uses vibration analysis to investigate the effect of the pump rotational speed on performance and detection of cavitation within a centrifugal pump. (Mousmoulis et al., 2019) also discussed the use of experimental analysis of cavitation in a centrifugal pump using acoustic emission, vibration measurements and flow visualization. (Abd-Elaal et al., 2019) uses condition-based monitoring (CBM) such as vibration analysis to monitor a healthy centrifugal pump and unhealthy centrifugal pump with defects such as broken impeller to show the difference in the vibration spectrum between healthy pumps and unhealthy pumps.

Based on the reviews made, it can be found that vibration analysis is a popular method used to identify faults in centrifugal pump and a good technique used for pump maintenance. In this work, the analysis of vibration characteristics in the centrifugal pump is carried out to investigate the vibration characteristic of centrifugal pump in healthy condition and also with the presence of mechanical fault and cavitation.

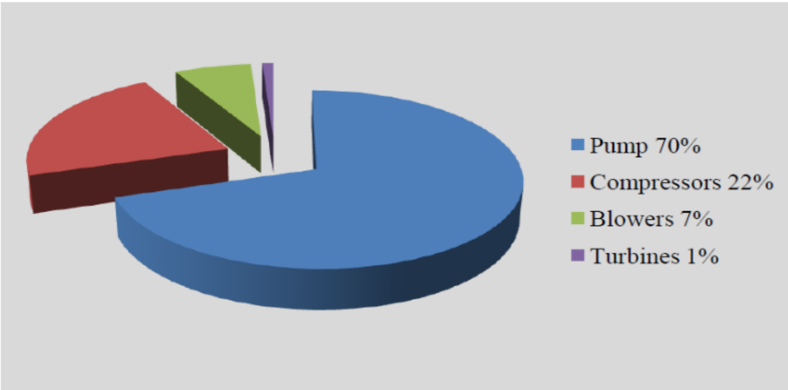

Figure 1.1: Cost of maintenance for different rotating machines (Ahmed Al-Obaidi, 2018)

1.1 Project Background

Centrifugal pumps commonly used in the industry typically fails due to a problem that arises within the fluid, such as cavitation and mechanical faults. Mechanical faults are found in the pump's bearings, nuts/bolts, impeller, and seals. The pump industry is dealt with a big blow due to this problem; pumps life length will be reduced due to this problem. This causes the industry to spend more on the unwanted problem and replacing the pumps with newer ones. Cavitation in the centrifugal pump has also caused the pump functionality to deteriorate. A few types of cavitation are found in the centrifugal pump, such as suction recirculation cavitation, in which turbulence of the fluid releases entrained gases into the suction piping. Vane passing syndrome cavitation is caused by the impeller being too small to cut water. Air ingestion on the pump's suction side allows air and bubbles into the pump's suction. Cavitation also occurs due to the clogged filter and pipe blockage on the suction side (Tiwari et al., 2020).

This cavitation and mechanical faults have caused significant problems to the pumps and industry, such as increasing vibration, noise and rapid deterioration of the impeller, seal, bearing, shaft, and motor. It also reduces the performance of the pump, which results in fluctuating flow rate and discharge pressure. In order to avoid this problem, it is advisable to identify the problem ahead and avoid unwanted situation. Therefore, vibrational monitoring of centrifugal pumps has been widely used in determining faults within the pump. Vibrational monitoring is crucial for us to understand the condition of the pumps using frequency spectrum. A vibration signal will be used to measure the frequency of the defects produced by cavitation. The vibration signal will be taken for a pump with a healthy condition, an unhealthy condition such as clogged flow, cavitation and mechanical looseness. Thus, the vibration signal obtained from the above conditions will be compared with parameters such as time domain and frequency domain.

1.2 Problem Statement

High vibration level in centrifugal pump may cause catastrophic failure to the pump, subsequently increase operation and maintenance cost. The condition monitoring centrifugal pump using vibration analysis due to cavitation and defect due mechanical faults has been reported in few research, however the vibration frequency due to this type of fault is rarely reported. There is a need to identify the vibration frequency produced by the faults in centrifugal pumps and establish the fault detection method using vibration analysis. The fault frequency can be used as an indicator of the pump health and provide early detection of fault or damage in pump before total system failure. This will reduce the problems caused in the industry area related to centrifugal pumps because there are many pump failures in the industrial area.

1.3 Objective

1. To evaluate the centrifugal pump vibration characteristics at a different flow rate
2. To investigate the vibration spectrum of centrifugal pump in a healthy and unhealthy condition
3. To identify the vibration frequency produced by cavitation and mechanical fault in centrifugal pump

1.4 Scope of work

The scope of work is to investigate two conditions of a healthy centrifugal pump and an unhealthy centrifugal pump. The study of vibration characteristics of centrifugal pump analysis is conducted to understand the behaviour of mechanical fault pump, cavitation in centrifugal pump and comparing it with a healthy centrifugal pump. Condition monitoring such as vibration analysis is used to analyse the centrifugal pump into time domain and frequency domain. The analysis of the centrifugal pump is carried out for a healthy pump, a cavitated pump, clogged flow pump and mechanical looseness in the pump. Two accelerometers which are horizontal accelerometer and vertical accelerometer is used to obtain the vibration level of the pump in terms of the vertical and horizontal direction. Vibration characteristics due to the different flow rates are also investigated. The study is conducted by vibration level monitoring and defect detection using spectrum analysis. The vibration analysis is performed using Fast Fourier Transform (FFT) to acquire the frequency domain signal from the time domain.

CHAPTER 2

LITERATURE REVIEW

2.0 General overview

Vibration analysis of the centrifugal pump is one of the techniques in identifying cavitation or any other defect in the centrifugal pump. Detecting cavitation or premature defect of the centrifugal pump will help us identify the centrifugal pump problems, which can prevent any failure in the rotating machinery. Therefore, condition monitoring of the centrifugal pump needs to be done from time to time to avoid any consequences. The detection of pump failure is usually done by carrying out vibration monitoring and noise level monitoring. This chapter reviews the vibration analysis of the centrifugal pump, cavitation detection and condition monitoring of the centrifugal pump.

2.1 Centrifugal pump working principle

The centrifugal pump is used to transport fluids by converting rotational kinetic energy typically from the electric motor to the fluid flow. The fluid enters the pump impeller which then accelerates and flow radially outward. The pump consists of multiple equipment such as volute and impeller which is mounted to a shaft. The shaft is then rotated by an electrical motor which transmits torque by the coupling. According to (Girdhar et al., 2005), if the pump is correctly primed, when the impeller rotates, accelerates, and displaces the fluid inside itself, additional fluid is sucked into the impeller to take its place. As a result of mechanical action, the impeller imparts kinetic or velocity energy to the fluid. The volute subsequently converts this velocity energy into pressure energy. The pressure of the fluid created in the casing must be confined, which is accomplished using a suitable sealing mechanism.

Furthermore, the purpose of the centrifugal pump is to pump the fluid around the suction and discharge of the pump. There are two main parts where energy change occurs, which is the impeller and the volute. Both of these parts change the kinetic energy into pressure energy. (Sahdev, 2012) also explained the process whereby liquid is drawn through the suction nozzle and subsequently into the impeller's eye (center). When the impeller spins, it accelerates centrifugal force by spinning the liquid in the spaces between the vanes outward. A low-pressure region is achieved as liquid exits the impeller's eye, prompting additional liquid to exit into the inlet

Moreover, helpful energy is usually pumped by the centrifugal pump to the fluid by changing the velocity as the fluid flow through the impeller and pump casing. (Nyi et al., 2019) explains that the liquid in the centrifugal pump is driven into a series of revolving vanes by atmospheric or other pressure in a centrifugal pump. A centrifugal pump is made up of a series of rotating vanes encased in a casing. A fluid's energy is imparted through a housing or casing by use of centrifugal force

(Maxime Binama, Alex Muhirwa, 2016) explained that the fluid enters the impeller eye axially where it is dispersed radially towards the inter-blade flow zones and tangentially whirling by the revolving impeller vanes. The momentum in the fluid also increases as the fluid flows pass through the rotating impeller. The fluid with high velocity is then converted to pressure which is used to overcome the head(m). The rotating impeller creates a vacuum at the impeller eye, which causes the fluid from the inlet to move into the impeller.

2.2 Vibration measurement

2.2.1 Time Domain analysis

(Dunton, 1999) explains that time waveform data analysis is not the latest invention. Time waveform data is usually seen on oscilloscopes, and frequency components were computed by hand in the early days of vibration analysis. Time and frequency can be related to the formula below:

$$f = \frac{1}{P}$$

where:

f is the frequency in hertz, and p is the period is seconds

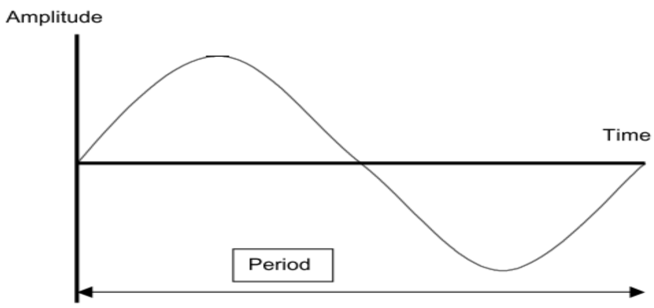

Figure 2.1: Graph of frequency vs time (Dunton, 1999)

The time waveform is used to obtain information regarding the condition of gears, rubs, sleeve bearing and to indicate the proper amplitude in the process where machinery defect occurs. By viewing the time-domain graph, defects or faults in the machine can be identified. The faults in the machine can be detected by observing the trends of the graph to give us the type of fault that has occurred in the machine

(Kumar & Manjunath, 2018) claims that time-domain analysis is done to investigate vibration information as a form of time. By analyzing the vibration or acoustic information collected from the accelerometer, time-space signals may be used to assess defect and fault. To investigate the arbitrary features of a vibration signal produced by a physical structure, factual techniques and highlight abstraction are commonly utilized. Further stochastic parameters are used for advanced signal utilization such as Standard Deviation, Root Mean Square, Peak Value, Crest Factor, Kurtosis, Skewness, Clearance Factor, Impulse Factor, Shape Factor, Upper, and Lower Bound Vibration value. (K M & T C, 2016) adds on that vibration analysis of spinning machinery can identify a wide range of system flaws. The vibration signal from good machines and malfunctioning machines highlights the difference in vibration signature. Even after the equalization, energy removal and filtering of time-domain data of rotating equipment include unbalance, rotor fracture, looseness, impeller defects, bearing defects, misalignment, high speed, rotor to stator rub, and flow whirl/whip.

(Vishwakarma et al., 2017) explains that Root Mean Square (RMS) and Crest are essential parameters used to diagnose faults in a rotating machine. A vibration signal's root mean square (RMS) value is a time-domain feature. It depicts the vibration's power content. When it comes to detecting imbalance in rotating machinery, the RMS value is beneficial. RMS value is the most basic method for detecting faults in rotating machines in the time domain, but it cannot detect faults when the problem is in its early stage. Another parameter in time domain vibration analysis is the crest factor. The crest factor is the ratio of the input signal's peak value to its RMS value. Peaks in time series signals cause the crest factor value to increase

2.2.2 Frequency Domain analysis

(Macfarlane, n.d.) uses frequency domain analysis to simplify analysis by breaking down a complicated signal into smaller pieces and to have a fast algorithm. Fourier transform is often used to change time-domain analysis to frequency domain analysis, and an inverse Fourier transform is used to switch frequency domain to time domain. The Fast Fourier transform (FFT) is more efficient than the Discrete Fourier Transform (DFT).

Based on (Commtest.com, 2006), a graphical display such as a spectrum graph is used to display the frequencies and amplitude for the vibrating machine component in the Fast Fourier Transform (FFT). The spectrum identifies us the frequencies at which the part vibrates and along with the vibration amplitude at what frequencies it is high. We may deduce a lot about the origin of the vibration and the machine's status by evaluating the particular frequencies at which a machine component vibrates and the amplitudes corresponding to those frequencies.

(Shreve, 1995) explains that Fast Fourier Transform (FFT) is a developed new technology used for further signal processing. It is a technique of breaking down time-varying signals into separate components to their amplitude, phase and frequency. Problems or defects can be spotted by connecting frequencies with machine features and looking at amplitudes. The swept filter is often used in analogue instruments to provide information. Filters are often used to eliminate specific parameters in the graph, such as low pass filters used to eliminate high frequency, while the high pass filters are used to eliminate direct current (DC) and low-frequency noise.

2.3 Vibration in Centrifugal Pump

(Abd-Elaal et al., 2019) briefs that vibration analysis of spinning machinery can identify a wide range of system flaws. The primary components of the spotted vibrational frequency spectra of rotating equipment include unbalance, rotor fracture, looseness, impeller defects, bearing defects, misalignment, high speed, rotor to stator rub, and flow whirl/whip. Vibration analysis is one of the types of condition monitoring in rotating machines such as the centrifugal pump.

(Albraik et al., 2012) adds on that mechanical and hydrodynamic factor both cause vibration in the functioning pump. Rotation of imbalanced masses and friction in bearings are generally the mechanical faults. Fluid flow perturbations and interactions of the rotor blades, notably with the volute tongue and guiding vanes, cause hydrodynamic vibration. The created vibration will cause the pump surface to shake, which will function as a loudspeaker, emitting noise into the air.

(Birajdar et al., 2009) concludes that sources of the vibration in the centrifugal pump can be divided into three causes of vibration, shown in the table below.

Table 2.1**:** Cause and source of vibration in centrifugal pump (Birajdar et al., 2009)

Cause of Vibration	**Source**
Mechanical	• Unbalanced rotating object
	• Damaged Impeller
	• Looseness in nuts/bolts
	• Worn out bearings
Hydraulic	• Operating above/below the best efficiency point (BEP)
	• Internal Recirculation
	• Turbulence in the machine
Peripheral	• Harmonic vibration from nearby equipment
	• Pump operating at critical speed
	• Temporary seizing of seal faces

2.4 Fault detection in centrifugal pump using vibration analysis

2.4.1 Cavitation detection in centrifugal pump

Detecting cavitation in a centrifugal pump is a demanding prospect done by many industrial owners and researchers. Many researchers used vibration analysis to identify and learn about cavitation in the pump. The articles below represent the vibration analysis used in detecting cavitation in the centrifugal pump.

(Al-Obaidi, 2019b) investigated on effect of pump rotational speed on performance and detection of cavitation within a centrifugal pump using vibration analysis. The vibration technique was used for the detection of cavitation in the pump. The parameters used in this experiment are various speed of the pump and various flow rate of the pump using the vibration technique. For the first part, various flow rates were used to predict the performance and cavitation, while the pump rotational speed was kept constant at N=2755 rpm. The size of cavitation varies with the flow rate and rotational speed, and it has been seen that the cavitation increases as the pump flow rate or pump rotational speed increases. This is seen when the rotational speed increases, the vibration amplitude also increases due to the cavitation occurrence within a centrifugal pump. Figure 2.2 shows the vibration frequency range under the waterfall frequency graph.

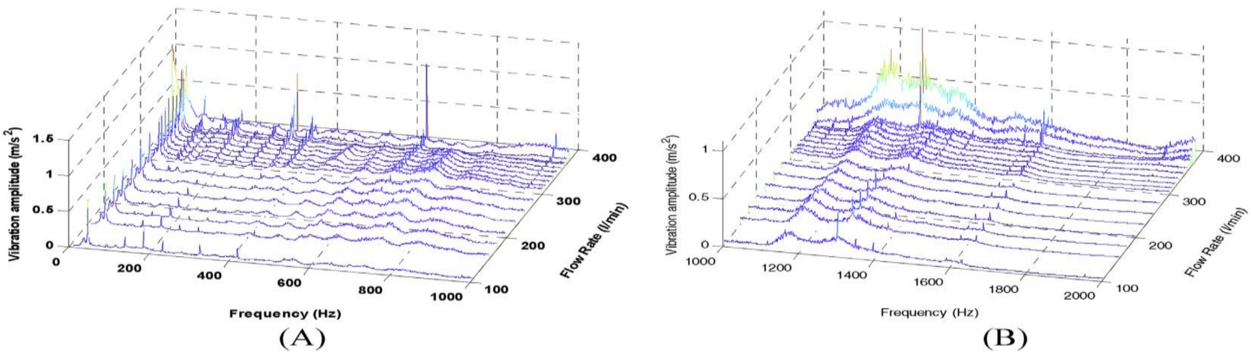

Figure 2.2: FFT spectrum under various flow rates and the vibration frequency range from (a) 0 Hz to 1kHz, and (b) 1kHz–2 kHz at 2755rpm. (Al-Obaidi, 2019b)

(Mousmoulis et al., 2019) worked on the experimental analysis of cavitation in a centrifugal pump using acoustic emission, vibration measurements and flow visualization. The author used three different types of impellers to study the development and detection of cavitation in different types of impellers where geometrical characteristics can affect the cavitation. The impellers will have a different number of blades, specific speed, and total head. It can be seen that the lower number of blades will result in a lower cavitation coefficient. Vibration on the pump also increases due to the increased number of blade, incidence angle, and pump flow intensity. This can result in an increasing number of bubbles and noise, and this can be seen from impeller 1 as it has a lower number of blades compared with impeller 2 and 3. The author concluded that different type of geometry of impeller blades affect the production of cavitation.

(Abdulaziz & Kotb, 2017) detected cavitation in a centrifugal pump by using vibration signature. The author tries to detect cavitation using constant rotational speed at different suction pressures located at five different points. The first and second point shows no sign of cavitation, but as the point increases, the third, fourth and fifth point show cavitation development. The discharge of water and Net Positive Suction Head (NPSH) is high as 78 kPa at the constant rotational speed of 2850 rpm. When the pump undergoes cavitation, it can be seen that the pump flow rate has lessened, its vibration level increases and also show higher frequency. As pump operation moves towards cavitation, the vibration level of discreet frequency at the pump rotational speed increases while it decreases for the discreet blade passing frequency (dBPF).

(Salem A. Al-Hashmi , Mohamed R. El-Hesnawi*, 2018) demonstrated the use of vibration signal in cavitation detection. The vibration of the pump is extracted by using an accelerometer. The author demonstrates the experiment by changing the flow rate while maintaining the pump speed at 2960rpm. Vibration signals were obtained for six different flow rates. It can be seen that cavitation starts at a flow rate of 340 liters/min and above. The signals of the vibration were processed in the time-domain and frequency domain. The amplitude spectrum is obtained by Fast Fourier Transform (FFT) in the frequency domain. Based on the Figure 2.3, pump vibration amplitude is high when the flow rate starts at 340 l/m even though it is in the low-frequency range. The author tried to detect cavitation in the low-frequency range to reduce the cost of the monitoring system.

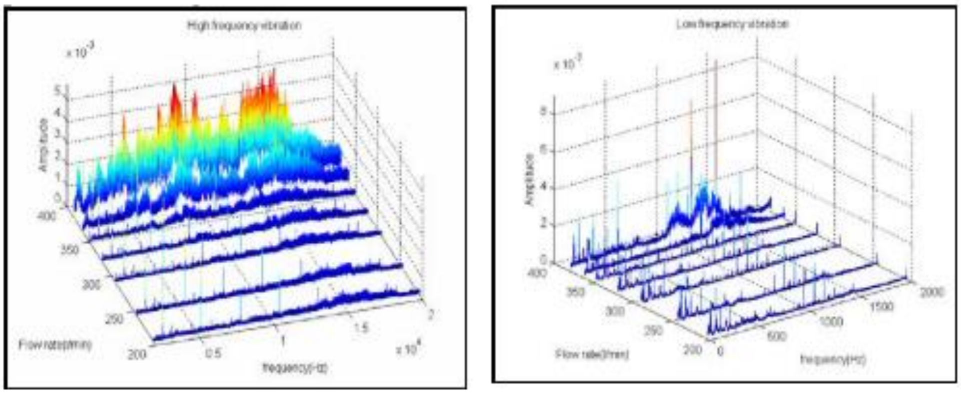

Figure 2.3: Waterfall frequency of high frequency and low-frequency range (Salem A. Al-Hashmi, Mohamed R. El-Hesnawi*, 2018)

(Ali et al., 2016) conducted a study on cavitation detection of the centrifugal pump using the Time-Domain method. The parameters that were used in this study was Kurtosis, RMS, Mean and Peak. The Data Acquisition system (DAQ) was used in this project to amplify and filter the signals for a proper sampling rate with analogue to digital converter. The vibration signal was taken from a pump with two conditions which is pump with healthy condition and pump with cavitation. From the study, it can be seen that the healthy condition pump, the amplitude is very low after 1000 Hz, but for the cavitation pump, it is the opposite. The cavitation pump shows the amplitude is high even after 1000hz and up till 3000hz. The author concluded that the value of RMS and peak at cavitation pump condition is greater than the healthy pump.

(Stephen, 2018) discussed the effect of cavitation in centrifugal pump and monitoring them using a vibration system. Based on the study, the author notices that cavitation already occurs before its performance characteristics been affected. The experiment is conducted with a constant pump speed of 1500 rpm and three different types of flow rates. The results and graph show that cavitation occurs at 3% head drop and at a high total head(m) of 20-25m. It is seen that vibration level increases with increasing speed as well as increasing flow rates. The author concluded that out of different vibration frequencies, repeatable frequency is far better than the predominant frequencies and the average magnitude between the frequency bands.

(Fajar & Widodo, n.d.) , conducted a study using vibration signature analysis in detecting cavitation in a centrifugal pump. The study was conducted using machine fault simulator (MFS) to conduct rotating machines such as centrifugal pump. The conditions of study used are varying pump rotating speed and varying opening suction valve at the tank. The pump speed was set at 1400 rpm, 2400 rpm, 3000 rpm and 3600 rpm with opening suction varying at 0°, 30°, 45° and 60°. Based on the results of measurement at discharge valve of 45°, it can be seen that cavitation occurs at high pump speed, which is 3600 rpm and also vibration frequency is high at 3600 rpm due to high vibration caused by cavitation. From another result, at 1400 rpm, the head (m) is reduced as Net Positive Suction Head (NPSH) was increasing, which also increases flow rate of pump. While at 3600 rpm, the maximum head of the centrifugal pump was reduced till 10m, flow rate was also not changed compared at 1400 rpm. The author proved that cavitation starts at a high pump speed and cavitation decreases total head (H), decreases Net Positive Suction Head (NPSH) of the pump and flow rate (Q) was not changed. Figure 2.4 shows the effect of speed on cavitation and frequency.

RPM	Pressure at suction (Psi)	Pressure at discharge (Psi)	F (Hz)	Condition
1393	-1	1	23,41	No cavitation
1400	-1	1	23,48	No cavitation
1401	-1	1	23,42	No cavitation
2394	-6	7	40,05	No cavitation
2400	-6	7	40,09	No cavitation
2401	-6	7	40,08	No cavitation
2999	-10	8	50,04	No cavitation
3001	-10	8	50,06	No cavitation
3006	-10	8	50,01	No cavitation
3594	-14	13	60,11	Cavitation
3598	-14	13	60,12	Cavitation
3600	-14	13	60,14	Cavitation

Figure 2.4: Varying pump rotational speed effect on cavitation and frequency (Fajar & Widodo, n.d.)

(ALTobi et al., 2019) performs an experiment that uses frequency domain analysis to monitor and diagnose the centrifugal pump condition. The author uses Fast Fourier Transform (FFT) as tool in detecting and identifying the types of faults produced in the pump. The vibration signals are measured for healthy and unhealthy pump. The unhealthy part is divided to mechanical fault and hydraulic fault (cavitation). The signal is obtained using an accelerometer and Data acquisition system (DAQ). The vibration signals are obtained at a speed of 1200 rpm with radial accelerometer and vertical accelerometer mounted to the pump for a speed of 2400 RPM and for horizontal accelerometer the speed is 1800 RPM. Fast Fourier Transform (FFT) spectrum for the healthy pump shows few significant peaks, but they do not show any signs of problems as they show very small signals compared to the unhealthy pump. Whereas for the cavitation pump produces high amplitude and random frequency vibration when compared with the healthy pump. Figure 2.5 and Figure 2.6 represent vibration analysis signal for healthy pump and unhealthy pump.

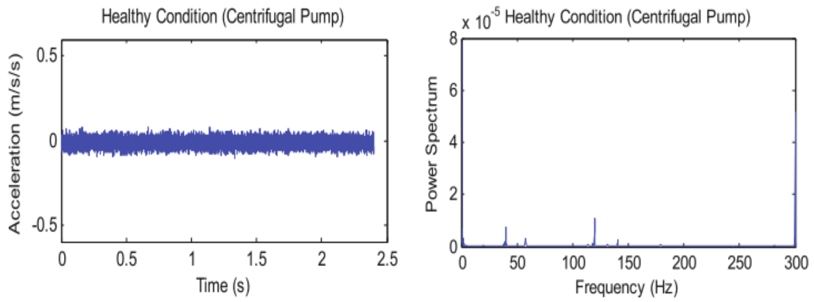

Figure 2.5: Time domain and frequency domain for healthy pump (ALTobi et al., 2019)

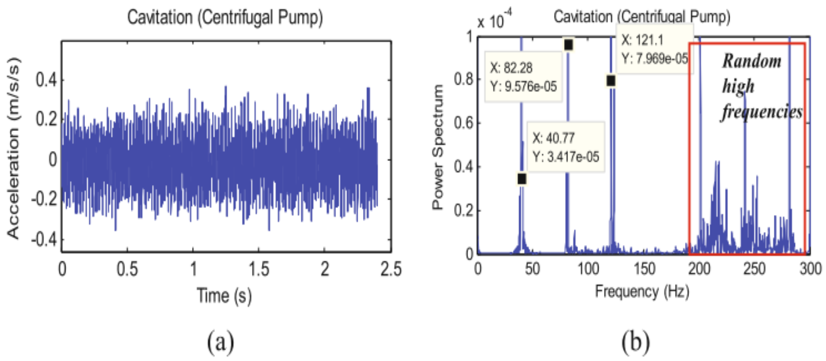

Figure 2.6: (a) Time domain and (b) frequency domain for pump with cavitation (ALTobi et al., 2019)

(Al-Obaidi, 2019a) in this experiment tests the performance and detection of cavitation of the centrifugal pump by changing the size of the suction valve opening. The author uses different sizes of the suction valve and different flow rates of 103 litres/min, 200 litres/min, and 302 litres/min with constant pump rotational speed of 2755 rpm. The author observed that the decrease in size of the suction valve opening causes the head (m) to reduce. Therefore, this causes the Net Positive Suction Head (NPSH) to lower and causes the head (m) to drop by 3%. Moreover, the cavitation increases with the head drop. The author analyses the acoustic signal in time domain in terms of Root Mean Square (RMS), peak to peak, peak, and variance to study the signal in more detail. For acoustic analysis, the Root Mean Square (RMS), peak to peak, variance value for acoustic amplitude increases as the size of the suction valve decreases. Based on the journal, the author described that a higher flow rate tends to start cavitation earlier because a higher flow rate tends to decrease the pressure in the inlet suction valve faster.

2.4.2 Impeller/imbalance fault detection

(Kiliç, 2016) conducted a study to identify imbalance problem in electric motor and centrifugal pump by using vibration analysis. The author picks the closest points to the bearing in the motor and pump as measuring points which uses the accelerometer as the measuring device. The measurements are done for three directions which are radial direction, tangential direction, and axial direction. Based on the findings, the amplitude value in the radial direction is higher than the amplitude for the tangential direction. The vibration plot from the pump free side and coupling side has a sinusoidal structure. The author concluded that the corroded fan blades caused the imbalance in centrifugal pump.

(Adamkowski et al., 2016) investigated the cause of the shaft breakdown in the centrifugal pump. Based on the author, it can be said that the shaft breakdown is mainly caused by the cavitation erosion to the pump impeller. This causes the resonance phenomena between pressure pulsations and torsional vibration. The cavitation had caused high weight loss in the pump impeller, which causes the moment of inertia of the pump to decrease. The erosion of the pump impeller blade had cause mass imbalance which causes the load exerted on the shaft to increase. The author proved that resonance of torsional vibration of the shaft caused from impeller erosion had caused the shaft to be fatigue and breakdown

(Albraik et al., 2012) tries to identify impeller faults in centrifugal pump using vibration method. In this experiment, the author uses five impellers where four impellers were defected with different size and one impeller was in good condition. The experiment was conducted with a constant speed of 2900 rpm with various flow rates. The author compared the good impeller with four different impellers with different sizes of gap. The healthy impeller has a gap of 3.2mm, while the rest of the faulty impeller had a gap lower than 3.2mm. It can be concluded; faulty impeller has higher head (m) than the good impeller with all flow rates. Next, the voltage remains almost the same for all flow rates but has increment for current and power for the faulty impeller. When the flow rate is above 275 litres/min the vibration amplitude for faulty impeller is higher than healthy impeller.

(Mahalik & Dastidar, 2012) detects fault in centrifugal pump using vibration and motor current signature analysis (MCSA) in his experimental study. The author uses different types of defective impeller with an impeller of one vane removed, another impeller with two vanes removed to identify the vibration signature. The author obtains results using an accelerometer and analyses the results in time domain, frequency domain and Fast Fourier Transform (FFT). The time-domain analysis of vibration signals showed that the peak and root mean square (RMS) vibration amplitude increases as the defect in the impeller increases. The author has said that severe defect of broken vane causes the flow in the pump to increase thus causing more vibration. The broken impeller also causes unbalance in the centrifugal pump. Based on the FFT graph, the author explains that the increase of defect in the impeller has caused the height of sidebands (SBs) to increase. Based on the time domain analysis of current signals, as the defect is severe, the current signal causes the vane passing frequency (VPF) to increase.

2.4.3 Mechanical looseness detection

According to (German-Sallo & Strnad, 2019)**,** there is a chance that mechanical looseness can occur at three locations which are internal assembly looseness, looseness at the machine to base plate interface and structure looseness. Internal assembly looseness can occur between a bearing liner in its cap and also at an impeller which is located on a shaft. This fault can be detected from the Fast Fourier Transform (FFT) graph as it produces many harmonics in the FFT because of the shaking of the loose part which causes exciting forces. Looseness will cause sub-harmonic multiples at ½ x rpm or 1/3xrpm.

Based on (ALTobi et al., 2019) research, the author investigates the use of frequency domain analysis for identifying various centrifugal pump conditions. The author uses a healthy and five other mechanical faults pump such as misalignment, imbalance, faulty bearing, faulty impeller and mechanical looseness to conduct the experiment. Based on the results obtained, the mechanical looseness fault in the pump produces high vibration harmonics in the Fast Fourier Transform (FFT) graph.

(Kiliç et al., 2017) uses predictive maintenance technique such as vibration analysis to identify failures in pump such as mechanical looseness. The author explains that the mechanical looseness occurs at either rotating element or stable elements. Based on the results obtained by the author, 1x RPM in the vibration graph may be an indicator for the mechanical looseness is present. It is also said that amplitudes in the time domain graph produced up to 20–25 mm/s^2 when the pump had mechanical looseness. Moreover, after the mechanical looseness fault was fixed the amplitude of the time domain graph went down to 9.19 mm/s^2 in radial direction. This proved that mechanical looseness in the pump could cause high vibration amplitude in the vibration spectrum.

(Lin et al., 2016) in this present work uses vibration analysis for monitoring the small centrifugal pump condition. The author experiments the vibration analysis using a healthy pump and unhealthy pump with defect such as unbalance, pedestal loose and impeller defect. The author uses accelerometer to obtain triaxial acceleration. The spectral domain, time domain and waveform were studied in the x, y and z-direction. The pump speed is run at 2850rpm (47.5hz) with various flow rate. Based on the study, the author observed that the highest amplitude from the graph of Fast Fourier Transform (FFT) would be at 50Hz, which is the pump motor speed used in this study. When the peak amplitude is at 50hz, there is a possible defect in the pump. Furthermore, if there is any peak amplitude vibration any higher than 50hz, it can be said that there is a defect in the pump

CHAPTER 3

METHODOLOGY

3.0 Overview

In this chapter, the characteristics of centrifugal pump, vibration monitoring, pump monitoring and cavitation identification techniques are discussed. The methodology of the project is shown in a brief flow chart below.

3.1 Pump priming

Before starting any operations regarding the centrifugal pump, pump-priming method is firstly done on the centrifugal pump. A centrifugal pump system has already been designed for this study. Figure 3.1 shows the experiment test rig which consists of a centrifugal pump.

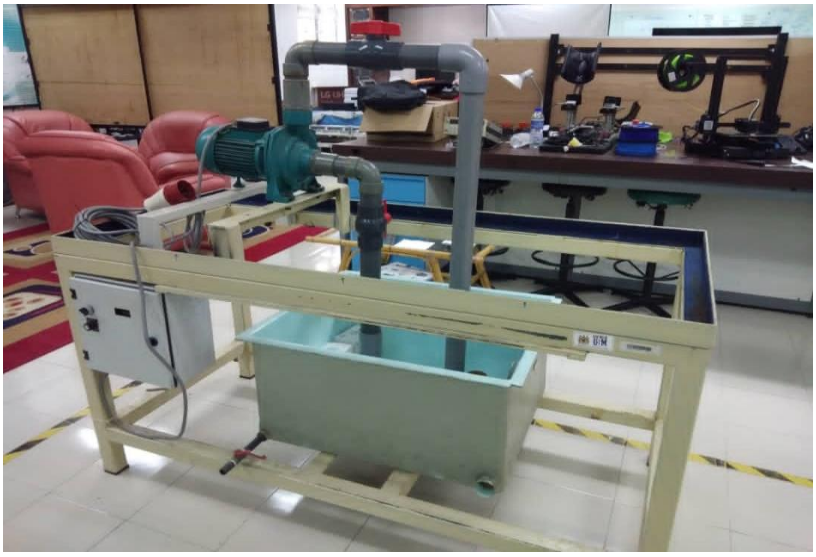

Figure 3.1: Experiment test rig of centrifugal pump

Pump priming is done to remove air from the pump and suction line (THEPROCESSPIPING, 2016). The pump is filled with liquid which forces all the air, gas or vapor contained in the passageway to be pushed out. According to recent studies, priming a pump is a necessary process to be done before starting up a pump. Priming will reduce the chances of damage during the startup of the pump because it prevents the pump impeller from becoming gas bound.

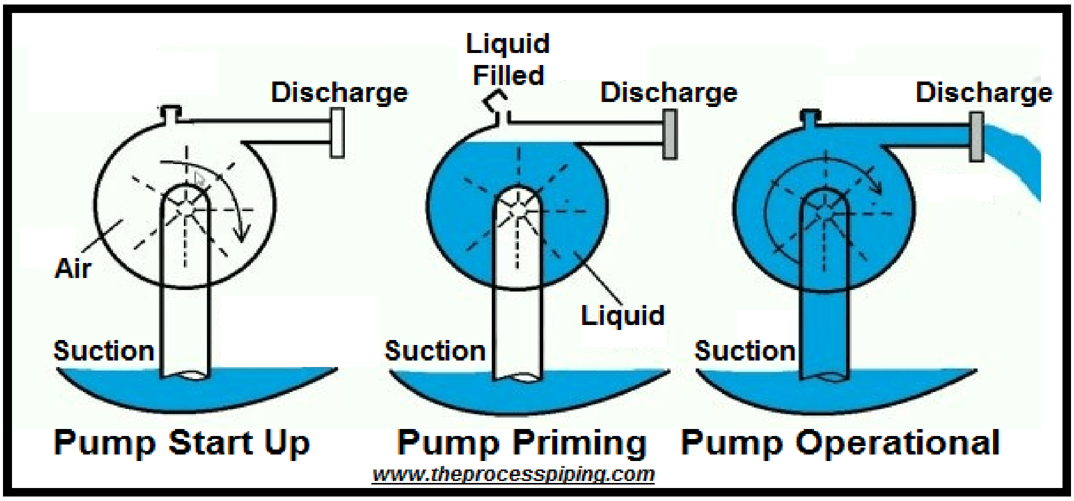

Figure 3.2: Pump priming operation (THEPROCESSPIPING, 2016)

To study the centrifugal pump vibration signal characteristics, a centrifugal pump is chosen for this experiment which is SEA PUMP DTM-20 Centrifugal Water Pump 2. The pump specification is shown in Table 3.1.

Table 3.1: SEA PUMP DTM-20 Centrifugal Water Pump 2 Specifications

Pump Body	Cast Iron
Impeller	brass/cast iron/aluminum
Motor	closed, externally ventilated
Insulation Class	B
Protection Class	IP44
Mechanical Seal	stainless steel/carbon-ceramic
Shaft	45# steel / stainless steel
Input Voltage	230V AC
Max Head Size	20m
Max Suction	9m
Inlet/Outlet Size	2 inches
Q Max	420 L/min
Rated Speed	2,850rpm
Rated Current	9.6A
Horsepower	2HP
Net Weight	22kg
Stage	Single-Stage

3.2 Analysis of vibration characteristics in centrifugal pump

The vibration analysis of the centrifugal pump is studied under different conditions, there are healthy pump (without fault); with mechanical faults (loose mounting): and cavitation due to blocked flow. The vibration signal is obtained in time domain and analyzed in the frequency domain by using Fast Fourier Transform (FFT).

The vibration signal of the centrifugal pump is measured by using an accelerometer (3055B2T DYTRAN instruments). The accelerometer was mounted horizontally and vertically at the pump casing near the impeller. The speed of the shaft was measured by using a tachometer device which is connected to the digital acquisition system (DAQ). The flow rate of the pump was adjusted using the ball valve where the closed valve depicts minimum flow rate while the open valve depicts maximum flow rate. The calibration of the accelerometer is done before running the pump. The signal from the accelerometer and tachometer is processed and analyzed with Simcenter SCADAS Mobile Data Acquisition System (DAQ) and LMS Test.Xpress software with a sampling rate of 64 kHz.

3.2.1 Analysis of healthy centrifugal pump

For the analysis of the healthy pump, the pump is operated at various speed, which is from 500rpm to 3000rpm, and with two different types of flow rate condition (minimum flow rate and maximum flow rate) by throttling the ball valve for the water to flow at the suction. Table 3.2 shows the range of pump rotational speed.

Table 3.2: Range of pump rotational speed for min flow condition and max flow condition

Pump rotational speed (rpm)					
500	**1000**	**1500**	**2000**	**2500**	**3000**

In this experiment, two different parameters will be adapted to run this experiment. The parameter will be for various flow condition and various pump rotational speed. For the various pump rotational speed parameter, the speed will be taken starting from 500rpm, 1000rpm, 1500rpm, 2000rpm, 2500rpm and 3000rpm with two different flow condition, which is minimum flow rate condition and maximum flow rate condition. The second parameter is with constant flow condition with pump rotational speed increasing from 500rpm to 3000rpm in 10second.

3.2.2 Analysis of mechanical looseness in centrifugal pump

For the study of mechanical looseness for the vibration analysis of the centrifugal, the bolt of the pump is loosened. The study was conducted with the parameters of various pump rotational speed and various flow condition. The various speed will be from 500rpm to 3000rpm with minimum and maximum flow rate conditions. Two accelerometers will be placed horizontally and vertically to obtain the vibration analysis. The vibration analysis will then be studied in terms of accelerometer mounting direction, to identify at which direction does the vibration affected the most. The study was conducted to identify the vibrational analysis of mechanical looseness and to be compared with the vibrational analysis of a healthy pump. The comparison of the analysis will be compared in terms of time domain and frequency spectrum of the healthy pump and pump with mechanical fault. Figure 3.3 shows the loosened bolt of the centrifugal pump.

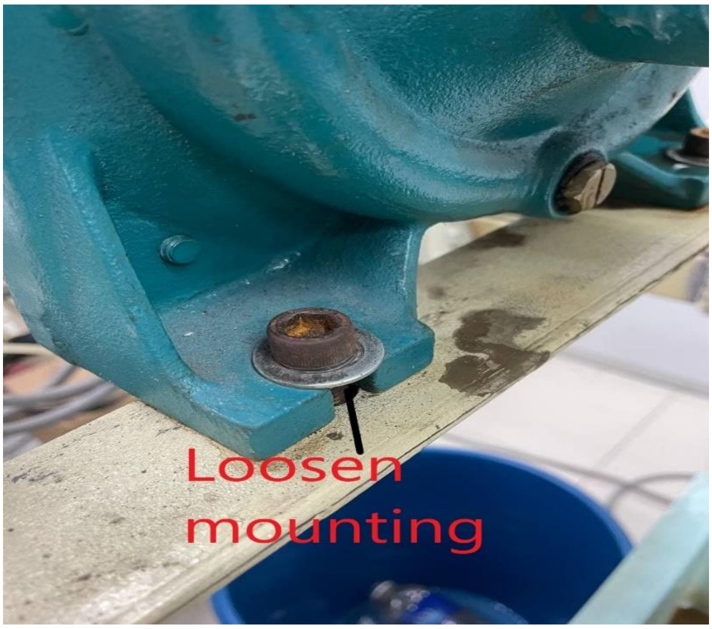

Figure 3.3: Loosen bolt of the centrifugal pump

3.2.3 Analysis of blocked filter in centrifugal pump

In the analysis of the blocked filter or clogged flow, the suction strainer of the filter suction is half-covered with plasticine to cause a blockage of flow in the centrifugal pump. Based on previous work, blockage of flow is one of the leading causes' cavitation occurrence in a centrifugal pump. The study was conducted to identify the effects of flow blockage on the production of cavitation and also to study the vibration characteristics of the flow blockage. The study was carried with some parameters such as various pump rotational speed and various flow conditions. The signal from the accelerometer, microphone and tachometer is processed and analyzed with Simcenter SCADAS Mobile Data Acquisition System (DAQ) and LMS Test.Xpress software. The vibration data obtained will be observed based on time domain and frequency domain using the FFT. Therefore, a comparison of analysis will then be made. Figure 3.4 shows the partially blocked flow of the suction strainer/filter.

Figure 3.4: The blocked filter covered with plasticine

Data Acquisition Device and System

Simcenter SCADAS Mobile is used in this study to get various values of parameters such as vibration levels, shaft speed, noise pressure etc. Simcenter SCADAS is used for testing productivity and covers a wide range of noise, durability, and multi-physics applications. The Data Acquisition System (DAQ) can accommodate up to eight to two hundred sixteen channels. The Data Acquisition System (DAQ) is designed specifically for high temperature and rough conditions. It also has a sampling rate of up to 204.8kHz. Data will be recorded and collected using this device and will be processed in the system software. Table 3.2 shows the specifications of the DAQ system used in this work.

Table 3.4: Specifications of DAQ system

• Accommodates 8 to 216 channels in a single frame
• Compact size and low weight for optimal mobility
• Rugged design qualified for rough conditions and high temperatures
• MIL-STD-810F qualified for shock and vibration
• Ultra-quiet operation, no fan cooling, ideal for acoustic measurements
• Supports IRIG-B and CAN-bus
• Up to 204.8 kHz sampling rate per channel
• 150 dB dynamic range
• High-speed ethernet host interface

Vibration accelerometer

The accelerometer used was 3055B2T produced by DYTRAN instruments. The accelerometer has a sensitivity range of 100 mV/g, which is suitable to be used in the centrifugal pump. The accelerometer was placed at the top and side of the centrifugal pump to measure vibration amplitude for the horizontal and vertical sides of the pump. The data obtained from the accelerometer will then be obtained by the Data Acquisition System (DAQ) to be processed. Figure 3.5 shows the position of the accelerometer, and the Table 3.4 shows the specifications of the accelerometer.

Figure 3.5: The position of the accelerometer attached to the centrifugal pump

Table 3.5: The specifications of the 3055B2T DYTRAN accelerometer

PHYSICAL	VALUE
WEIGHT	8.6 grams
SIZE, HEX x HEIGHT	.50 x 0.62 inches
MOUNTING PROVISION	10-32 UNF-2B X .200 deep
CONNECTOR, RADIALLY MOUNTED	10-32 coaxial
MATERIAL, BASE, CAP & CONNECTOR t	titanium
SEISMIC ELEMENT TYPE	ceramic, planar shear
SENSITIVITY, ± 5%	100 mV/g
RANGE F.S. FOR ± 5 VOLTS OUTPUT	±50 g

Figure 3.6 shows the flowchart of the overall research done in this project. The vibration characteristics is obtained for three types of conditions of centrifugal pump which are healthy centrifugal pump, pump with mounting fault and pump with blocked filter. These conditions are evaluated using vibration level and FFT frequency spectrum. Comparison of vibration characteristics is made by comparing healthy pump with unmounted pump and blocked flow pump.