



Investigation of effect of pump rotational speed on performance and detection of cavitation within a centrifugal pump using vibration analysis



Ahmed Ramadhan Al-Obaidi*

Department of Mechanical Engineering, Faculty of Engineering, Mustansiriyah University, Baghdad, Iraq

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ABSTRACT

Cavitation is an essential problem that occurs in any pump. It highly contributes to deteriorating the performance of the pump. In industrial applications, it is important to detect and decrease the effect of the cavitation in pumps. In this work, detecting and diagnosing the cavitation phenomenon within centrifugal pumps using vibration technique was investigated. The results obtained for vibration signal in both time and frequency domains were analysed in order to gain a better understanding about the detection of cavitation in the pumps in question. The effect of different operating conditions including various flow rates and pump rotational speeds related to the cavitation were measured. Different statistical features in time domain analysis (TDA) and also the Fast Fourier Transform (FFT) technique for frequency domain analysis (FDA) were applied.

1. Introduction

The origin of vibration in centrifugal pumps might occur from various types of sources, including hydraulic and mechanical excitation forces [1, 2, 3, 4, 5, 6]. This leads to an increase in the levels of vibration that might decrease the performance of the pump and hence results in causing damage in the pump parts such as the impeller and volute. It may also lead to decreasing the pumps bearing life and the seal failures [7, 8, 9, 10]. The measurements of vibration in centrifugal pumps can be utilised for several applications including quality control and condition monitoring (CM) [11, 12, 13]. The hydraulic and mechanical sources of vibration in centrifugal pumps occur as a result from several problems. This comprises problems of flow distribution including high velocity, and interaction between the rotating part such as impeller and the stationary part such as the volute through the rotation of the impeller in the pump particularly at volute tongue region. Furthermore, hydraulic sources of vibration in centrifugal pumps includes blades passing forces, hydraulic imbalance, recirculation flow, cavitation, system instabilities, water hammer and so on [14]. Generally, as described in the experimental setup in study four, the pumping system comprises several parts. This pumping system includes the centrifugal pump, an electrical motor and its related flow loop piping system such as pipes, elbows, fittings, and

valves. Even through regular operation conditions, various kinds of physical processes create vibration such as hydraulic interaction with the piping system, improper installation or maintenance, application for the pump, and manufacturing designs and different types of faults [15]. Typically, the mechanical vibration sources in the pump includes several sources such as pressure fluctuations created in the fluid, imbalance, misalignment between shafts connections, and damaged bearings [16]. In addition, other mechanical sources incorporate mechanical forces, improper usage of the pump as provided in the installation manual and the conditions emerging from the pumps' incorrect assembly and from wear [17, 18]. When cavitation occurs in the different types of machines (e.g. propellers, turbines, and various kinds of pumps), it leads to dropping in pressure particularly at the eye of the impeller below the water vapour pressure. As a result, this leads to increasing the level of noise and vibration due to unstable flow which, in turn, causes an increase in the pressure fluctuations within a pump [15]. When cavitation starts to occur within the pump, the first formations of bubbles are very small leading to the bubble collapse inside the pump. As cavitation continuous inside the pump, the bubbles collapse then occurs close to the surface of the impeller, which eventually erodes the impeller and hence, causes pitting on the surface of the impeller and volute. Because the formation and collapse of bubbles happen randomly, the incipience and development of

* Corresponding author.

E-mail address: ahmedram@uomustansiriyah.edu.iq.

cavitation can cause high noise and vibrations within the pump [15]. Over the last decade, there have been increasing interests in using condition monitoring (CM) methods for detecting cavitation. There are several reasons behind this method as it decreases the costs of machines maintenance and hence, enhance productivity and safety in the industry. In this study, the vibration signal is analysed as it is one important technique in the condition monitoring of centrifugal pump in order to early predict and diagnose the inception and development of cavitation occurrence within the pump. Also in this research, the vibration signals would be collected via the use of an accelerometer (vibration sensor) that has been positioned close to the volute tongue region of the centrifugal pump. The reason behind selecting this position is because this is a part in the pump that has high effect due to the high interaction between the rotating part (impeller) and stationary part (volute) as clearly shown that in previous study. For this experimental work, in order to study the wide range of operation conditions and also to detect the different levels of cavitation, the centrifugal pump has been subjected to various flow rates and pump rotational speeds the pump. The flow rate has been changed by throttling the ball valve at the discharge pump side and then adjusted step by step. Furthermore, the analysis of vibration signals under different above operation conditions using time domain analysis (TDA) and frequency domain analysis (FDA) are performed using MATLAB code in the next sections. The sources of vibration in the centrifugal pump during different operational conditions has been evaluated and then the revealing of how the incipience and development of cavitation influences the pump vibration level. Furthermore, it presents and discusses the experimental outcomes of using vibration technique for monitoring cavitation within the centrifugal pump on the experimental setup. Also, the study would provide an analysis of the vibration signals in time domain using time wave form analysis (TWFA). Then, it uses various statistical features such as peak, RMS, peak-to-peak and variance values in order to predict and diagnose the cavitation phenomenon under various operation conditions. For further analysis of the characteristics of cavitation phenomenon inside centrifugal pump, the vibration signal in time domain is converted to frequency domain analysis (FDA) through the use of (FFT) technique which can be suitable in predicting and diagnosing cavitation in the pump. This study further focuses on analysing the vibration signal in frequency domain based on different range of frequencies. Furthermore, it analyses the vibration amplitude in frequency domain by using different features such as mean and RMS on the vibration amplitude values. This analysis is essential in order to obtain a better understanding and also more information regarding the detection of the occurrence of cavitation within a pump for various frequency ranges, and thus finding the sensitive frequency range for predicting cavitation. Cavitation flows in centrifugal pumps have been investigated in the literature using various approaches to predict cavitation conditions as two-phase flow. These studies are by Zhang et al. [19] which studied the vibration features in centrifugal pump that has a special slope in the volute. In their work, they have proposed and analysed vibration characteristics in the pump with a special slope volute to decrease the vibration and offer a new technique to decrease vibration level in the pump. They gained vibration signals at various flow rates and the compared between the slope volute and conventional spiral volute pump. The results have shown that the vibration level of slope volute pump was lower than the conventional pump as illustrated in figure under different frequency. Therefore, they have found using slope volute pump it can be decrease efficiently the vibration level in the centrifugal pump. Suhane [20] studied the effect of radial clearance on pressure pulsations by using vibrations and noise signals in the centrifugal pump under different flow and radial clearances between impeller and diffuser 1.5mm, 3.7mm, 6.8mm respectively. The author used horizontal type pump with diffuser the impeller designed with eight blades and the diffuser composed of seven blades. As a result, at low flow rate both vibration and noise levels were low and they high under high flow rate, as well the vibration and noise levels were minimum at the maximum radial clearance between impeller and diffuser. In addition, the author observed that from

experimental outcomes when increasing the radial clearance, the lower pressure fluctuations occur. Farokhzad et. al [21]. experimentally investigated the relationship between vibration signal and fault diagnosis within the centrifugal pump under different operating using conditions monitoring system. They have been tested two different configurations the first one was broken impeller and the second one was faulty seal conditions. They collected vibration signals from the pump using the accelerometer sensor which was positioned on the in the bearing of the shaft. The results have shown that an important change in the trend of vibration signal as a function of fault at various operating conditions. The value of RMS for healthy pump conditions was on suitable status, but it was increased due to the broken impeller and seal faulty on critical status. Luo et al. [22] researched on statistical features of vibration signals in the centrifugal pump. The parameters of the test pump were flow rate 50 m³/h, head 32m, rotational speed 2900rpm, the number of blades 6, impeller inlet and outlet diameters 75mm, and 174mm respectively. The results have shown that when the pump works under flow instability conditions, the dynamic characteristics of the pump were changed. Therefore, the statistical analysis of vibration signal (probability density factor PDF, Standard deviation, and Kurtosis) could be a useful technique of predicting unstable flow in the pump. The statistical features of vibration signal in time domain and frequency domain are a good indicator for predicting intensity changes and the onset of cavitation in the pump. Tan and Leong [23] experimentally studied detection of cavitation in the centrifugal pump using vibration signal. They tested the pump under three operating conditions including BEP, 90% of BEP and 80% of BEP. The design parameters of the pump were six vanes, and the motor was coupled to three phases with pump rotational speed of 2500rpm. The results have shown that the vibration amplitude was a significant increase under cavitation as compared to normal operating condition. The possible reason for the increase the vibration amplitude during cavitation was due to the formation and collapses the bubbles particularly in the eye of an impeller. Zargar [24] detected cavitation within the centrifugal pump related oil industry for cooling circulation water system. They have detected cavitation phenomenon within a pump using condition monitoring system by analysis the vibration signal in time wave form and frequency domain using FFT method. They have found that the trend of vibration signal was suddenly increased under cavitation. Hence, decrease in the performance of the pump. As seen in the above studies and after looking at as well as studying the literature presented in this work the flow field and cavitation phenomenon in the centrifugal pump need more investigation. Therefore, in this current work, the hydraulic pump performance and the internal flow of the centrifugal pump are analysed under different operation conditions. The effect of various flow rates and pump rotational speeds on the performance, internal flow and detection of cavitation in the centrifugal pump are experimentally carried out based on vibration analysis technique. Moreover, the vibration signal within a centrifugal pump in both time and frequency domains are also investigated in order to obtain more information regarding the detection of cavitation in the pump using various Statistical Features. Furthermore, studying different frequency ranges in frequency domain analysis (FDA) on cavitation detection within the centrifugal pump also investigated. The Experimental Setup for the Centrifugal Pump.

The main aims of this present study are to determine the pump performance and detect cavitation in the centrifugal pump experimentally. The detection of cavitation experimentally has been achieved by using vibration through the use of accelerometer as well as pressure using two pressure transducers at suction and discharge of the pump under the different range of operation conditions. To achieve this aim experimentally, it was essential to construct and design an appropriate experimental setup for the centrifugal pump, where the designing of this experimental setup would be discussed in more details in the next section.

Fig. 1 depicts the main different experimental setup components of test rig setup of the centrifugal pump. The centrifugal pump can supply water to the tank with a maximum pressure about 10bar. The selected flow loop system was re-circulatory and included a plastic water tank,

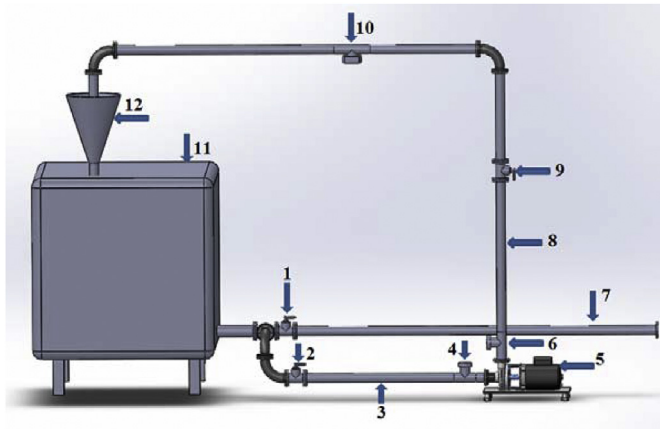


Fig. 1. Centrifugal pump flow loop including: 1- Main flow loop inlet valve, 2- Centrifugal pump inlet valve, 3- PVC suction pipe, 4- Inlet pressure transducer, 5- Centrifugal pump, 6- outlet pressure transducer, 7- Main suction pipe flow loop, 8- PVC discharge pipe, 9- Discharge valve, 10- water flow meter, 11- Water tank, 12- Hopper.

PVC clear pipe and PVC connections components. The tank capacity has been based on the maximum flow rate. The inlet pipe diameter of the pump is 2 inches. Also, the outlet pipe diameter of the pump used is 1.25 inches. Thus, a reducing coupling of 1.25–1.5 inches has been used to connect the outlet pipe to the water flow meter line because the diameter of water flow meter is 1.5 inch. The tank is made of plastic with dimensions of $95 \times 90 \times 110$ cm. The entire section pipes are a transparent pipe the reason behind that is to permit observation when the cavitation occurs. There are several reasons behind selecting the latter type of pipe. Firstly, the clear pipes are easier to install. Secondly, they are easy to connect them and thirdly they are low cost as compared to the stainless-steel pipes. Furthermore, the PVC pipes do not necessarily allow for complicated tools to be used in connecting the different pipes together, as the entire connections between pipes are made using a solvent welding type (solvent cement and cleaning fluid) However, the PVC clear pipes have some disadvantages such as lack of rigidity. The connections of the flow loop of the centrifugal pump and the water tank are made through use of various sizes of PVC pipes [25, 26].

2. Experimental

2.1. Effect of various flow rates to predict the performance and cavitation within a centrifugal pump

For analysis purpose in this study, vibration technique has been used in order to predict cavitation. The centrifugal pump was operated experimentally at different flow rates (three stages of flow rates). The first stage was at low flow rate, and the second stage was at design flow rate and the last stage was at high flow rate as summarised in Table 1. Pump rotational speed $N = 2755$ rpm was kept constant corresponding to $0.95N_d$, where N_d represents the design pump rotational speed and it is equal to 2900rpm, due to the maximum pump rotation speed for this experimental setup which was 0.95 of N_d . The next section presents the results of the pump performance and predicting cavitation that have been obtained from experimental calculation based on the different flow rates.

One key aim in this experimental study is to calculate the pump head. Therefore, several experimental measurements have been conducted to

find the pump performance under various operation conditions. Furthermore, the suction and discharge pressures signals of the pump can be obtained through the use of two pressure transducers at suction and discharge sides of the centrifugal pump. The data includes pressure signals and calculated head are processed through use of MATLAB code as shown that in next section.

2.2. Analysis on the instantaneous outlet pressure of the centrifugal pump under various flow rates

Fig. 2 depicts the raw data of the instantaneous outlet pressure from the centrifugal pump in time domain, under different flow rates starting from 103 (l/min) to 378 (l/min) with pump rotational speed of 2755rpm. It can be seen that the instantaneous outlet pressure signals changes as the flow rate also change. Moreover, the magnitudes of the pressure fluctuations decrease with increases in flow rate. The possible reasons behind that are due to the hydraulic and mechanical losses as well as the effect of the occurrence of cavitation leading to causing more unstable flow within the pump. However, it can be observed that these changes in the instantaneous outlet pressure do not provide a clearer picture regarding the detection of cavitation in the pump. Therefore, further investigations are then required to detect cavitation using different statistical features in order to analyse the instantaneous outlet pressure signals in time domain in the next section.

2.3. Calculate the head and NPSH of the centrifugal pump under various flow rates

Time domain analysis (TDA) is used to analyse the raw data of the instantaneous head under various flow rates with different statistical features. Fig. 3 depicts the trend of peak, minimum and RMS features for the head under different flow rates from 103 (l/min) to 378 (l/min) with pump rotational speed of 2755rpm. It is evident that the above mentioned head features in the pump all follow a downward continuous trend with increasing flow rate due to the same reasons given above. Moreover, the trend for all the above features rapidly decreases when the pump operates at flow rate higher than 350 (l/min). The reasons are because of the high interaction between impeller and volute and due to the occurrence and development of cavitation within a pump.

Fig. 4 depicts the mean head of the pump under various flow rates measurements which has also been summarised in Table 1-with a pump rotational speed of $N = 2755$ rpm. From this figure, it can be clearly be seen that the changes in the pumps' flow structure as flow rate increased from lower to the higher value and the interesting point is here to notice the change of head in the pump. It can be observed that the trend of head gradually decreases when flow rate increases. Moreover, from this figure, it can be seen that the head is changing in a periodic manner as the pressure changes in the pump. Due to three main possible reasons, the first one is due to the high interaction between the impeller and tongue volute region which generated by the impeller rotational speed. The second reason is related to the non-uniform distribution of pressure distribution in the volute due to the asymmetrical cross-section area of the volute, and finally, the important reason is the occurrence of inception and development of cavitation within the pump. Moreover, it can be seen also from this figure that when the pump operates under high flow rate, it leads to decrease in the head within the pump and then also lead to reduction in the pressure at the inlet eye of the impeller below the water vapour pressure. Hence, that leads to cause cavitation phenomenon, and it will develop in the pump when the flow rate is increased. Further investigation also shows that the head rapidly decreases when

Table 1

Range of flow rate for the pump under pump rotational speed of 2755rpm.

Range of flow rate (l/min)																
378	370	365	362	352	342	331	320	310	302	276	252	227	200	177	152	103

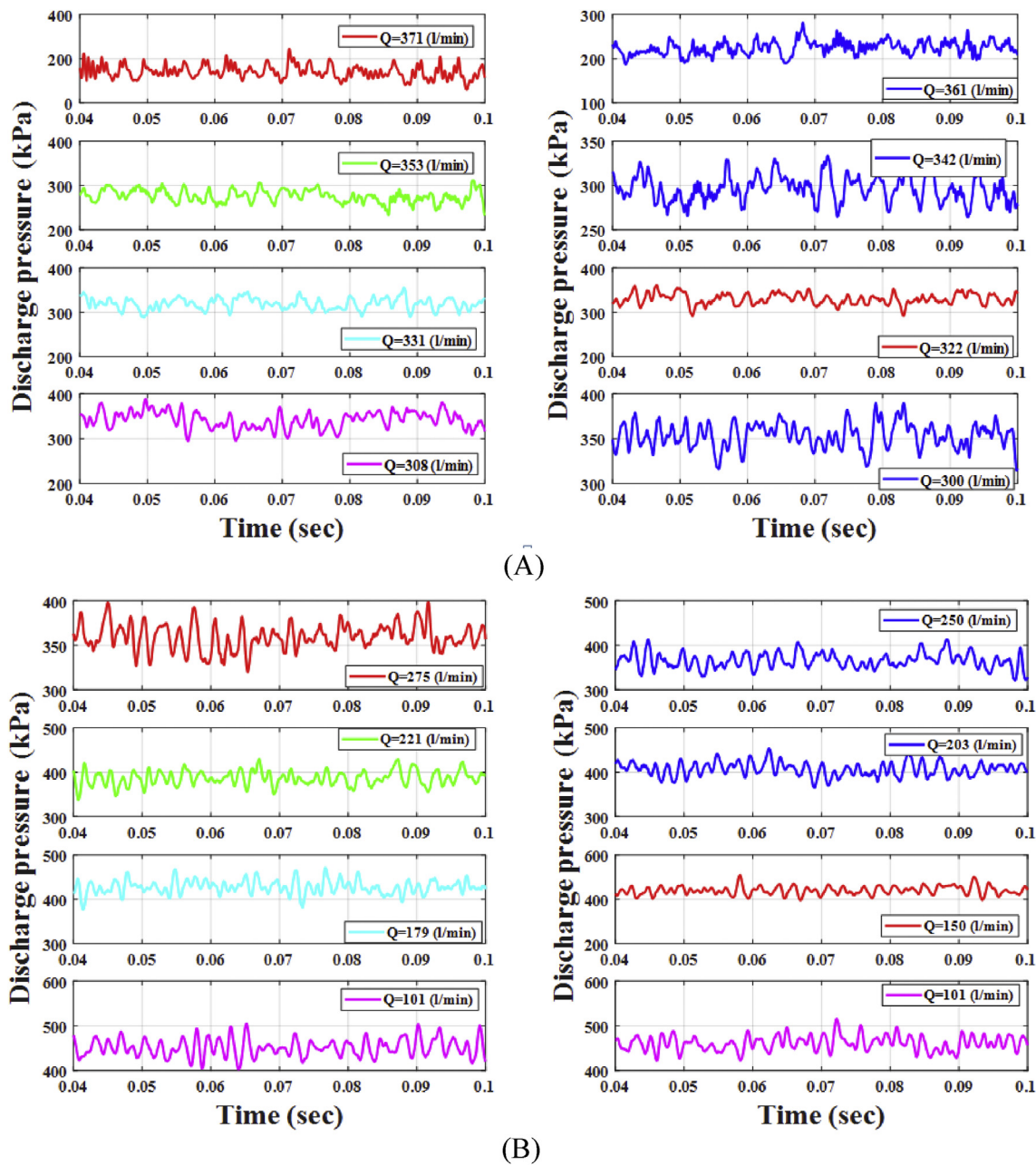


Fig. 2. A) Discharge pressure of the centrifugal pump from 371 to 300 (l/min), B) From 275 to 101 (l/min) at pump rotational speed of 2755rpm.

the pump operates at flow rate higher than 350 (l/min). The reason is because of the occurrence and development of cavitation. However, this phenomenon will be analysed and then discussed in detail in this study using the vibration technique.

The effect of cavitation phenomenon on the output performance of the centrifugal pump under different operation conditions would be discussed. Such conditions would include various flow rates and different pump rotational speeds using vibration analysis technique. It is essential to first investigate and then calculate the Net Positive Suction Head NPSHa of the centrifugal pump so that the relationship with the different flow rates can be described, as well as also establishing a general knowledge of the pumps' performance. In this experimental study, the centrifugal pump has been tested under different measurements of flow rates corresponding to normal operation conditions (without cavitation conditions) and with cavitation conditions. The cavitation characteristics of the centrifugal pump that are monitored as important part of this study

are plotted in Fig. 5. This figure depicts the Net Positive Suction Head available, and Net Positive Suction Head required against different flow rates based on inception and development of cavitation in the pump [27]. For this purpose, the pumps' flow rate can be changed through progressively throttling the discharge valve and then keeping the suction valve open at 100% and keeping the pump rotational speed constant at 2755rpm. The experimental data for the H-NPSHr curve for the centrifugal pump has been provided by the manufacturers (Pedrollo company pump model F32/200H).

From this figure, the different regions of cavitation are quite apparent. The first one was when the pump works under low flow rate making no cavitation to occur in this region. At this point, the NPSHa is higher than the NPSHr. For the second region, the flow rate is higher than 350 (l/min) and at this region, cavitation begins to occur in the pump where the intersection between the two curves for NPSHa and NPSHr already occurred. That means the development of cavitation starts at this

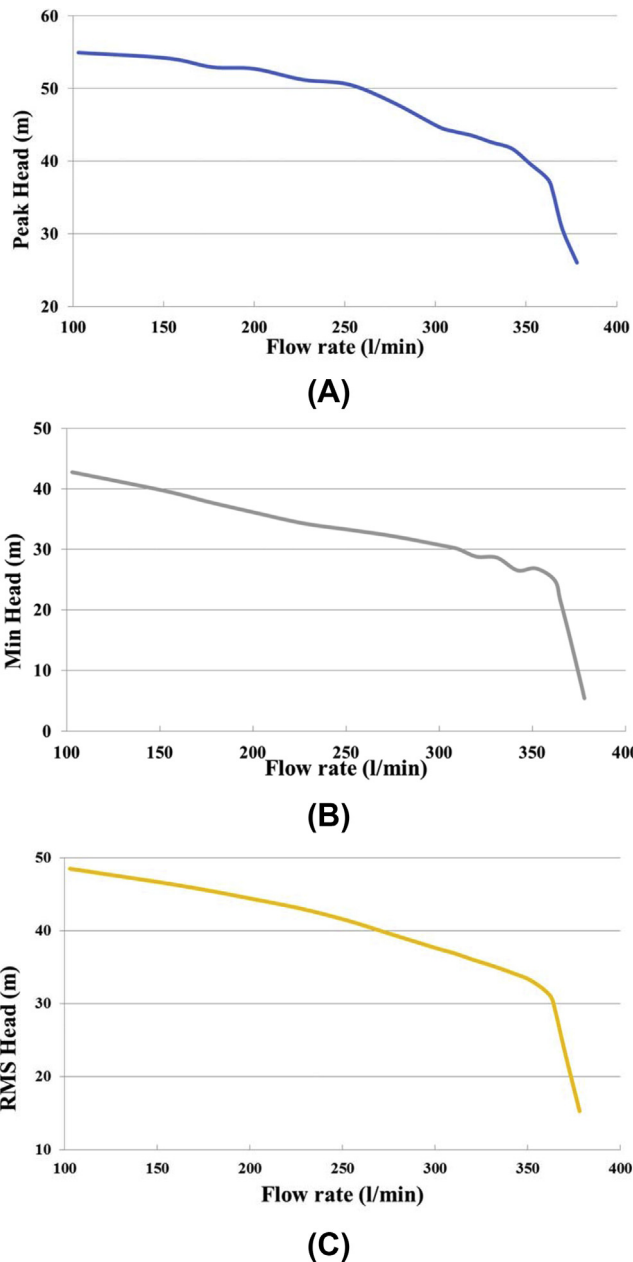


Fig. 3. A) Peak, B) minimum and C) RMS features of the head under different flow rates and pump rotational speed of 2755rpm.

point. The third important region is when cavitation within the centrifugal pump starts to increase as the flow rate increases more than 350 (l/min) due to decrease in the pressure at the eye of the impeller below the water vapour pressure and hence, at this point, the NPSHa becomes smaller than the NPSHr. Also, it is clear that the signs of cavitation include deteriorating of the performance of the pump. Additionally, during the experimental measurements for the centrifugal pump, inception of cavitation rapidly deteriorated at the flow rate higher than design flow rate. Also, it can be seen from this figure that cavitation has occurred at flow rate between higher design flow rate range of 300 (l/min) and 350 (l/min). As well as it can be clearly seen that the level of cavitation was increased with the flow rate increased. Furthermore, based on the above results regarding the relationship between the NPSHa and NPSHr with the pumps' flow rate, it can be seen that the value of NPSHa and NPSHr have a high effect on the performance of the pump. In this current study, investigation and discussions regarding the performance of the

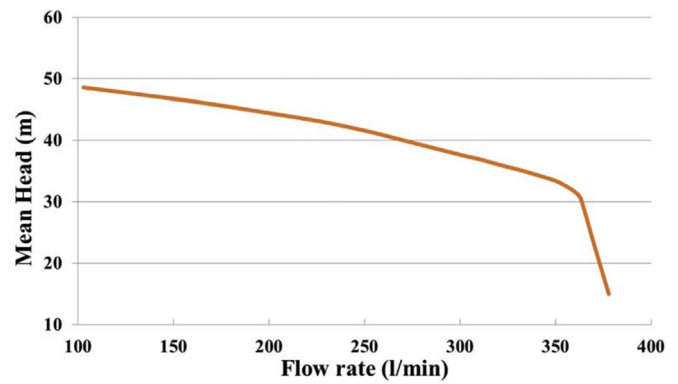


Fig. 4. Head of the centrifugal pump under pump rotational speed 2755rpm.

centrifugal pump under cavitation conditions have been carried out using vibration technique. The details of the influences of various experimental operating conditions including different flow rates and pump rotational speeds are discussed and analysed in detail in the following sub section.

3. Results and discussion

3.1. Predicting cavitation within a centrifugal pump using vibration technique under various flow rates

In this research, an attempt has been made to investigate the pumps' behaviour under the effect of normal operating and cavitation conditions through the application of vibration technique. This technique necessitates a particular sensor such as accelerometer sensor and an accurate signal evaluation processing technique. The purpose was to analyse the vibration signal related to cavitation condition within a pump under different operating conditions. Moreover, results corresponding to the vibration signal under various flow rates, through calculations and analysis of the signal amplitude in time and frequency domain within the pump, have been presented to predict and diagnose cavitation. Simultaneous evaluation of the different experimental measurements based on normal operation (without cavitation) and detection of cavitation conditions have been performed using MATLAB code. In this study and through the experimental tests, the vibration signals are collected using an accelerometer sensor as mentioned earlier. Furthermore, the performance of the centrifugal pump parameters such as discharge flow rate,

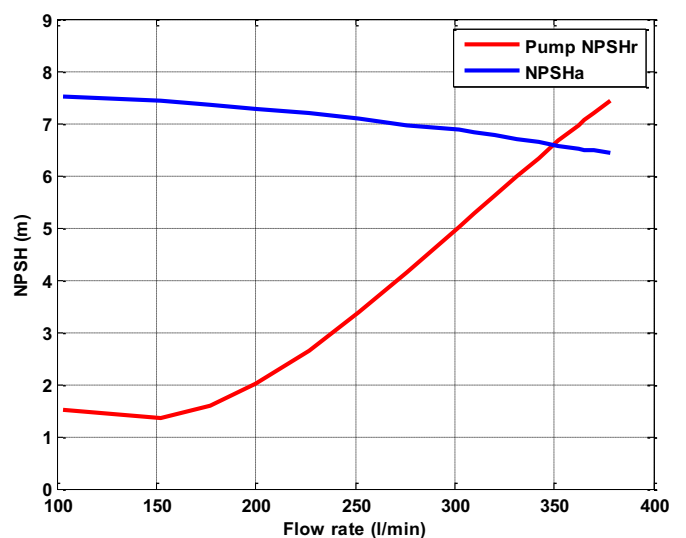


Fig. 5. The cavitation characteristics of the centrifugal pump under different flow rates.

inlet, and outlet pressure are measured through the use of various types of sensors including water flow meter, two pressure transducers at suction and discharge sides of the centrifugal pump. The various types of signals from all above sensors are sampled, collected and saved through the use of data acquisition type dynamic data acquisition and analysis system model YE7600 from Global Sensor Technology (GST) which made by SNO-CERA PIEZOTRONICS. In this experiment, the pump was in operation for each test under the different flow rates. The capacity of the centrifugal pump has been divided depending on the flow rate at the different regions. Region one was at the low flow rate starting from 100 to 250 (l/min). The second region was at design flow rate 300 (l/min), and the last region was at high flow rate higher than design flow from 320 to 378 (l/min), and the range of these flow rates depended on pump rotational speed.

During each experimental test for the vibration signal sampling process, the pump rotation speed was kept constant at the different flow rates. In these experimental measurements, each experimental test has been repeated at least 3 times. In order to obtain and provide more reliable consistent data sets, collecting and repeating each operation test will help to comprehend the characteristics of the vibration signals and hence, acquire more dependable diagnostic features in predicting cavitation within the pump. This study would collect and then analyse the vibration signals under various flow rates. These signals were obtained and collected through the use of the sensor such as an accelerometer type CA-YD-1182. At the input of the voltage signal obtained from the accelerometer has been collected then sampled at 96kHz in the data acquisition system. Furthermore, the numbers of data points in each of these experimental measurements were equalled to 2880000 points. Of recently, in order to measure vibration in the system, an accelerometer has been widely used as the most appropriate vibration sensor. There are several reasons behind using this type of sensor. Firstly, it can be used for wider ranges of frequency. Secondly, it is easy to install on the machine. Thirdly, it is reliable for vibration measurement and finally, it can be used effectively to predict various conditions such as healthy or faulty equipment. Currently, there are many applications associated with pumps in the industry. Therefore, condition monitoring in pumps has become a significant application as it can allow the extension of the life of the pump as well also decrease the cost of maintenance. In this research, a methodology has been proposed in detecting the inception and development of cavitation within the centrifugal pump. This firstly methodology that would be discussed in this study is based on the vibration signal analysis methodology in both time and frequency domain under different operation conditions. Fig. 6 depicts the flow chart analysis of the vibration data for detecting cavitation within the pump. In this study, the vibration analysis methodology has been suggested for detecting the inception and development of cavitation within a centrifugal pump. Based on signal processing monitoring system through the use of vibration signal, under a wide range of operation conditions. Such conditions include different flow rates and pump rotational speeds. The methodology has been used in this research which consists of different stages and the brief details of this experimental stages are as follows:

- > The first stage includes collecting the experimental test measurements of the raw vibration signals from the centrifugal pump under the different ranges of operating conditions using accelerometer.
- > Analysing the vibration signal based on time domain (TD). First compare the various raw vibration signals under the different operation conditions using the graph of the time wave form analysis (TWFA). Second is to then analyse the vibration signal by using different statistical features such as peak, RMS, peak-to-peak and variance values.
- > Detect various levels of cavitation (no cavitation, inception, development, and full development of cavitation) within a pump by using above features.
- > Compare between above-mentioned features to find the sensitive feature in order to detect different levels of cavitation.
- > Analysis the vibration signal based on frequency domain (FD) using FFT technique firstly, analysis the raw vibration signal based on various frequency ranges (low and high-frequency ranges).
- > Find the sensitive frequency range for detecting different levels of cavitation in the pump using waterfall figures (three-dimension figures) to compare between vibration signals under different conditions.
- > Analysing the amplitude of the vibration signal under different frequency ranges and wide range of operating conditions based on frequency domain (FD) using different statistical features such as mean and RMS vibration amplitudes.
- > Detect different levels of cavitation (no cavitation, inception, development, and fully development of cavitation) within a pump by using above features.
- > Compare between above features in order to find the sensitive frequency range in frequency domain analysis (FDA) in order to detect different levels of cavitation within a pump. Furthermore, all above stages have been processed using MATLAB code.

The details of analysing the vibration data in time and frequency domain under different range of operation conditions and frequency ranges using above methodology are presented and discussed in the next sections.

3.2. The vibration signal analysis based on time domain (wave form) under various flow rates

In the time wave form analysis (TWFA) of vibration acceleration signal have been compared under normal and cavitation operating conditions. The experimental results have been depicted and grouped based on different flow rates. The cavitation phenomenon within a pump can be detected using condition monitoring system by time wave form analysis (TWFA). Different vibration waveforms signals collected by accelerometer sensor that is mounted on the centrifugal pump casing are illustrated in Fig. 7. This figure depicts the relation between the amplitude and time for the vibration waveform signals under various flow rates for different operation conditions were considered which are normal operation conditions without cavitation and abnormal operation conditions with cavitation are listed in Table, and pump rotational speed of 2755rpm. It can be seen from this figure there are different levels of vibration amplitudes according to the change in the flow rate. For example, when the pump works under the low range of flow rate such as, between 152 and 302 (l/min) the levels of vibration amplitudes are almost the same. It is also worth noticing that at a low range of flow rate the levels of vibration amplitudes are lower than that when the pump operates under high flow rate. However, at the high range of flow rate for example, from 331 to 352 (l/min) the vibration levels begun to increase. Obviously, at the range of flow rate from 362 to 378 (l/min) the values of vibration amplitudes rapidly increase, the results depict that the vibration amplitude signal increases with flow rate increases. Two possible reasons can be considered behind this phenomenon. The first one is due to the high interaction between the impeller and volute tongue region such interaction occurs particularly in this region due to two important reasons. The first one when the trailing edge blades of the impeller are near and then they crossed the tongue region during rotation of the impeller, and the second reason when the tongue area was in between two trailing edge blades of the impeller. The second main reason to increase the vibration amplitude is mostly due to the incipient cavitation phenomenon taking place at the high flow rate, and it will develop when the flow rate is increased. In this case, the trend for the vibration amplitude was more random with high peaks when compared with normal operating conditions. The reason behind this is that when cavitation occurs in the pump, it generates very small bubbles and these small bubbles collapse and hence, leads to changes in the shape and amplitude of the vibration signals. Furthermore, it can be seen that the occurrence of cavitation is one key reason that causes instability in the flow within a pump. By

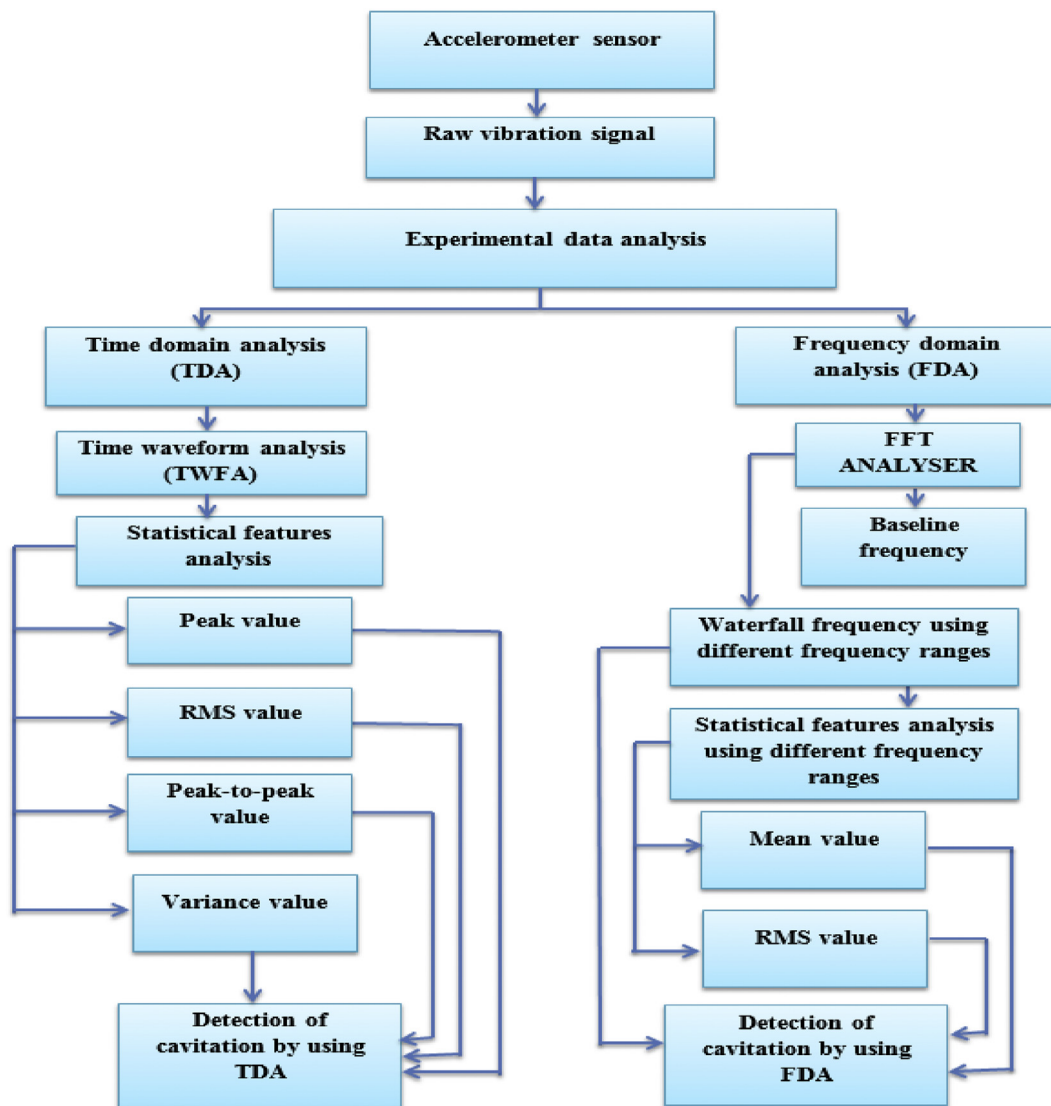


Fig. 6. Flow chart analysis of vibration data processing.

comparing between figures (a) and (p), it can be concluded that vibration signals are sensitive to predicting cavitation within a pump.

As it is evident in above figure, the change in the level of vibration amplitude varies according to flow rate changes. However, such variances have revealed that the useful evidence concerning information regarding for detecting cavitation phenomenon within a pump using time wave form analysis (TWFA). For extraction of useful raw data features, statistical analysis is used in condition monitoring (CM) method, which depends strongly on the kind of signal under investigation. In order to obtain further information with regards to analysing the vibration signals, this section has analysed the vibration signal in time domain through the use of various types of statistical features such as peak, RMS, peak-to-peak and variance values. In order to obtain clear idea regarding how the vibration amplitude is changed under different flow rates, and hence to predict and diagnose the cavitation phenomenon within a centrifugal pump under various operation conditions. Furthermore, the analyses above features are performed using MATLAB code. The level of vibration stability of a pump is associated with the pump flow rate. For this study, the design of experimental setup for the centrifugal pump loop system can operate under different operation conditions.

3.3. Analysing the vibration signal using peak and RMS values in time domain

As mentioned earlier, to analyse the sample of vibration signals under various operation conditions, different statistical features of vibration signals have been used in time domain analysis (TDA) including peak and RMS values. The peak and Root Mean Square (RMS) value function in the vibration signal has been a useful function for monitoring condition systems. These statistical features are widely used in condition monitoring in referring to the signal energy content. The calculation of RMS value is obtained through the use of an equation as given in study four. The raw vibration data are obtained from experimental setup and then processed in time domain. Fig. 8 depicts the analysis of vibration signal for a centrifugal pump using above statistical values. In order to detect the inception and development of cavitation conditions, various types of operation conditions of flow rates such as at low flow rate from 100 to 250 (l/min), design flow rate at 300 (l/min) and high flow rate from 320 to 378 (l/min) has to be conducted with the pump rotational speed kept constant at 2755rpm. It can be seen that from these figures there is a small indication of the variance in vibration level at flow rates below 350 (l/min). Though, at a flow rate above 350 (l/min), the vibration level witnesses a significant increase. However, the results from the experimental measurements have showed that the same trend occur for all the

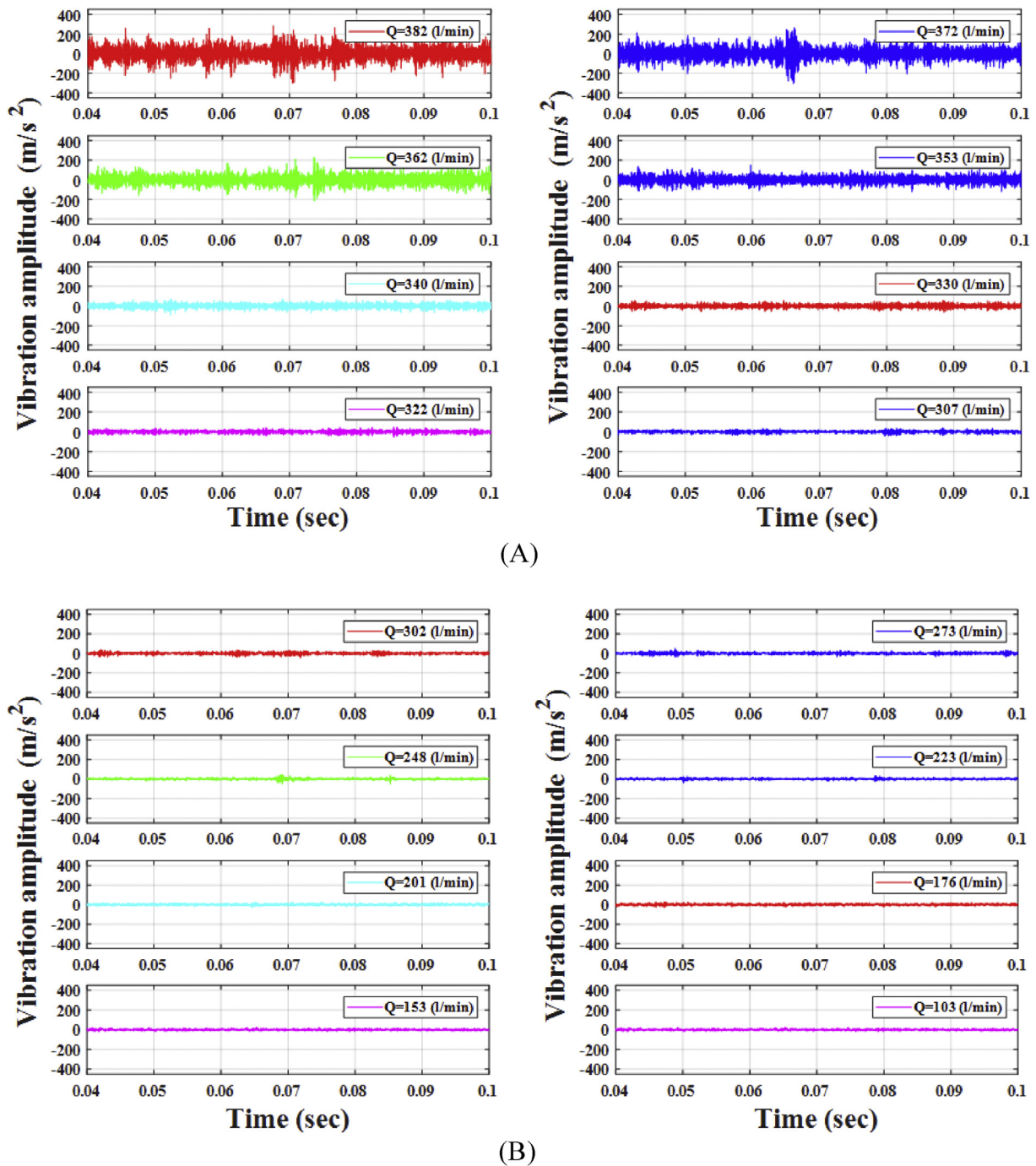


Fig. 7. A) Vibration amplitude from 382 to 307 (l/min) and B) from 302 to 103 (l/min) at 2755rpm.

statistical features on the vibration signals under the different flow rates. All of these statistical parameter trends, rapidly increases, when the centrifugal pump operates under flow rate of 350 (l/min). One of the main reasons is because of the occurrence of cavitation at this particular flow rate. The second reason is due to the interactions between the impeller and volute tongue region which then results to the pressure fluctuations reaching the highest peak inside the pump occurring very close to this tongue region. However, the values and levels of the pressure fluctuations inside the pump increase or decrease in magnitude as the trailing edge blades of impeller is near or far away from the volute tongue region. Moreover, it can be noticed that for flow rate between 100 to 300 (l/min), the RMS value is approximately lower than that of the peak values as seen in Figure This is due to the flow instabilities within the

pump under high flow rate. Furthermore, it can be noticed that the rapidly starting value increase was earlier for the peak feature as compared to the RMS feature. The results depict that using peak and RMS features in time domain analysis (TDA) have the capability in order to predict cavitation in the centrifugal pump under high flow rates. Due to the characteristics of cavitation in centrifugal pumps, as illustrated in earlier sections in Figure, it was obvious that when the flow rate was higher than design flow rate, it led to inception of cavitation of the pump. On this basis and from above findings it can be concluded that cavitation was the central problem behind the increase in the level of vibration in the centrifugal pump. Hence, the vibration signal analysis in the time domain can be considered as an indication to first determine the pump's condition, in addition to when cavitation has occurred in the pump.

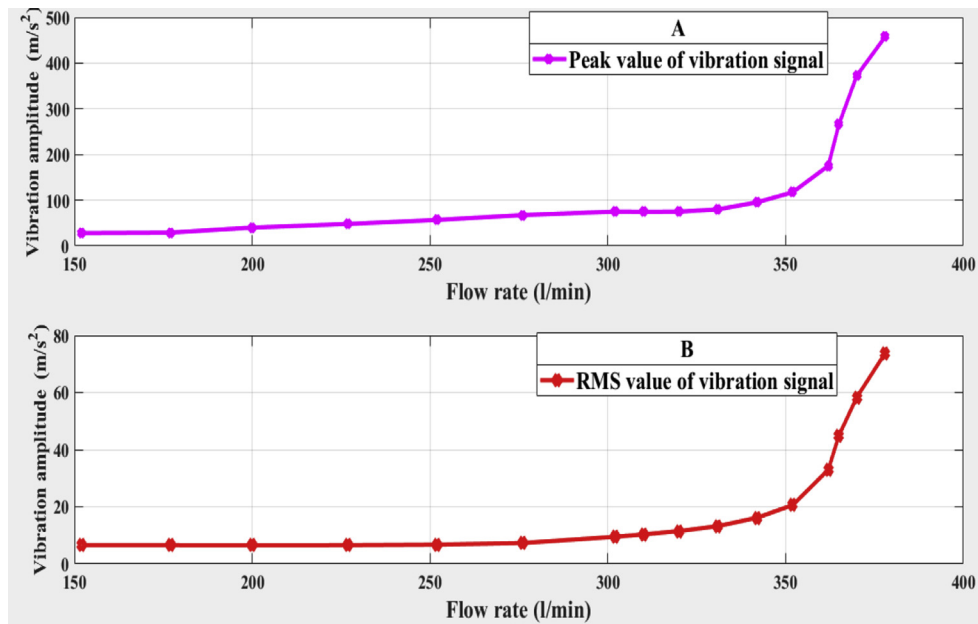


Fig. 8. A) Peak and B) RMS values of the vibration amplitude in the centrifugal pump at 2755rpm.

Additionally, the peak feature value was more sensitive as compared to RMS feature for detecting occurrence of cavitation. The investigation of vibration signals through the use of peak and RMS values offer useful information regarding a centrifugal pump condition. Hence, analysis of the trend of vibration amplitude, together with the flow rates could provide a good indicator for detecting cavitation. Consequently, different statistical parameters to monitor the trend of vibration amplitude such as peak-to-peak and variance values can be used to predict cavitation as we would see in next section.

3.4. Analysis of the peak-to-peak and variance values based on time domain (TD)

The relationship between the vibration level and various flow rates within a centrifugal pump can provide more information regarding the detection of cavitation through the use of other different types of statistical features trends such as peak-to-peak and variance values. The variance value can be calculated through using the equation given in study four. For further analysis, the vibration signals in time domain for the centrifugal pump in Fig. 9 depicts the peak-to-peak and variance values, under various flow rates, under a pump rotational speed of 2755rpm. It can be clearly seen that from these figures that the values of peak-to-peak and variance have approximately the same trend as compared to the trends of peak and RMS values. It can be observed that there is no significant change in peak-to-peak and variance values when the centrifugal pump operates under low flow rate from 100 to 300 (l/min). Also, as seen at a flow rate beyond 350 (l/min), the vibration amplitudes witnessed a fast increase as shown in these figures. For comparison between different flow rates, the level of vibration amplitude has been rapidly changed with the increase of the flow rate value particularly in the flow rate from 350 to 378 (l/min). When the centrifugal pump operates at low flow rate, while the pump rotation speed is kept constant at 2755rpm, it can be observed that no cavitation occurred. While at the same rotational speed but under high flow rate, inception of cavitation then begins to occur at the pump and as the flow rate increases continuously, cavitation then also increases leading to the pump working under a fully developed cavitation. In other words, it can be seen that when the NPSHa is smaller than the NPSHr, that leads to cavitation occurrence. Furthermore, it can also be observed that the peak-to-peak

value increase rapidly when compared to the variance value. From the above finding, it can be concluded that the peak-to-peak value was more sensitive as compared with variance value. Also, the result shows that the use of statistical features such as peak-to-peak and variance values in order to analyse the vibration data in time domain acquired from experimental measurements can be a suitable technique to identify the inception and development of cavitation in the pump under different operation conditions. Based on the above results, it can be observed that the occurrence of cavitation within a pump was the important reason to increase the level of vibration amplitude.

The analysis of vibration signals using peak, RMS, peak-to-peak, and variance values in time domain show rapid increase at flow rate 352 (l/min). Based on above results, vibration amplitude can be used as the threshold to detect cavitation and hence, this threshold can be used to identify the different levels of cavitation within a pump. Furthermore, the analysis of variation in the levels of vibration amplitude, within a centrifugal pump under different experimental measurements of flow rate in time domain analysis (TDA), agreed with characteristics of cavitation that has been presented using the NPSH curve.

Based on the above investigation, it can be seen that the analysis of vibration signals amplitude, using different statistical features in time domain have approximately the same trend when compared with the characteristics of cavitation that has been presented using the NPSHr curve. The NPSHr and vibration signals increase as the flow rate also increases. In order to further quantify the vibration signals using the different statistical features, Table 2 summarises the peak, RMS, peak-to-peak, and variance value under different levels of cavitation conditions at various flow rates and pump rotational speed of 2755rpm. It can be seen that the values of all above statistical features of the vibration signal are increased as the level of cavitation increases, which follow the same trend as that of the NPSH curve. That due to when cavitation process occurs in the pump, and it will develop at the high flow rate that leads to cause unstable flow and hence increase the pressure fluctuations as a result that lead to the increase the level of noise and vibration. Furthermore, the results have shown that the severity of cavitation has different levels increase. No cavitation at the low flow rate 103 (l/min), inception at 331 (l/min), development of cavitation at 352 (l/min), and obviously the highest-level of cavitation (fully development) occurs at 378 (l/min). It can be concluded that from above results the level of

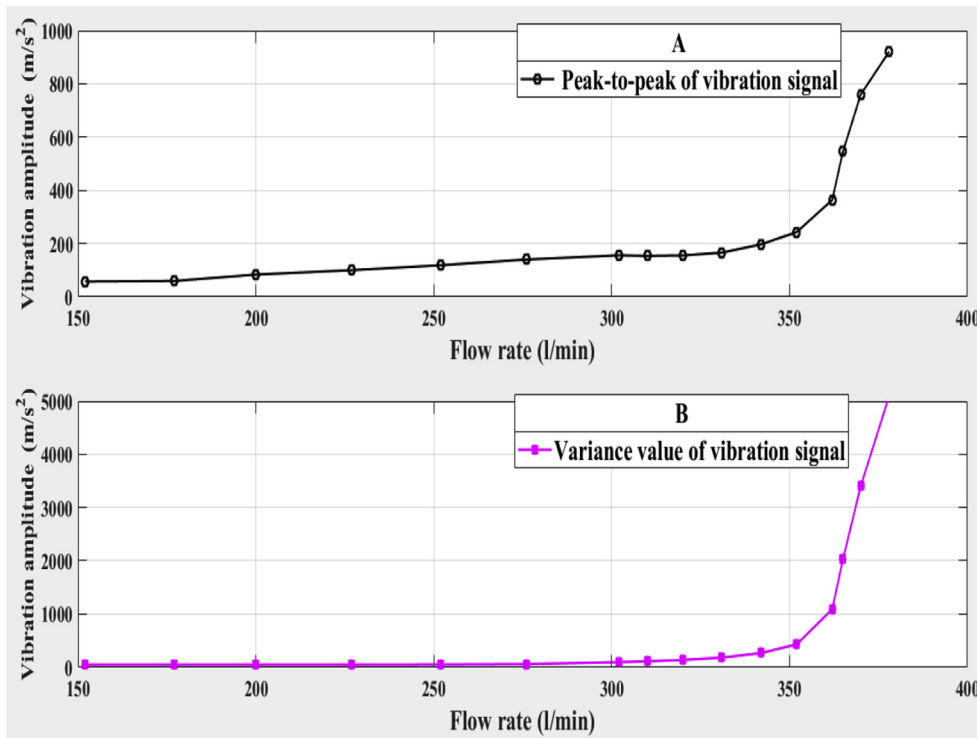


Fig. 9. A) Peak-to-peak and B) variance values of the vibration amplitude within the centrifugal pump at 2755rpm.

vibration stability and severity of cavitation within a pump is directly associated with the pump flow rate.

During the experimental tests of the centrifugal pump, it can be clearly noticed that the vibration signal changed in time domain at flow rate higher than 350 (l/min) that mean at this point the pump was operated under cavitation conditions the main reason behind that is due to the NPSHr was higher than NPSHa. Furthermore, based on the characteristics of cavitation within a centrifugal pump, and the analysis of vibration signal in the time domain that depicted in the above figures. It can be observed that the cavitation was the significant reason to increase the vibration of the pump, and hence based on vibration signal investigation, it can be concluded that the analysis of vibration signal in time domain analysis (TDA) provides the initial indication to predict the cavitation in the pump. Therefore, for more investigations and understanding in order to predict and diagnose the inception and development of cavitation in the centrifugal pump more specific features are required. These features can be found through transforming and analysing vibration signals in the frequency domain (FD) by using of Fast Fourier Transform (FFT) technique. The details of analysis vibration data in frequency domain under different range of flow rates and frequency ranges are presented and discussed in the next section.

Table 2

Peak, RMS, peak-to- peak, and variance value under different levels of cavitation conditions at different flow rates and pump rotational speed of 2755rpm.

Severity of cavitation	Flow rate (l/min)	Peak value (m/s ²)	RMS value (m/s ²)	Peak-to-peak value (m/s ²)	Variance value (m/s ²)
No Cavitation	103	30.78	6.71	63.43	45
Inception of cavitation	331	79.88	13.25	165.87	43.3
Development of cavitation	352	117.40	20.61	242.86	175.6
Fully Development of cavitation	378	457.66	73.82	921.14	5099.6

3.5. The analysis of vibration signals based on frequency domain (FD) under various flow rates

As mentioned in the previous section, the level of vibration signal amplitude highly depends on the operating conditions of flow rate inside the pump. The results from time domain analysis have revealed that when the pump is being operated under low flow rate that is less than the design flow rate, a minimum level of vibration will occur. But when the pump is working under condition that is higher than the design flow rate, more vibration and noise occurs. This is attributed to several reasons but one reason is mostly because of the interactions between the impeller blades and part of the volute tongue, close to the tongue region. Another reason can be due to increase in turbulent flow within the pump. The most important reason is due to the cavitation phenomenon that has occurred at high flow rate. The vibration signals have been collected through the use of an accelerometer sensor. The cavitation phenomenon in the pump can be identified by finding the variation in vibration signal amplitudes as would be discussed in detail in the next section.

3.6. The analysis of baseline frequency in the centrifugal pump

Fig. 10 depicts the frequency of the vibration signal for the centrifugal pump under design flow rate 300 (l/min), and based on the range of frequency 0Hz to 1kHz and pump rotational speed of 2755rpm. It can be seen that from this figure, the frequency ranges between 0Hz and 1kHz and the characteristics of the frequencies that have occurred in the pump are due mostly to the periodicity in the flow within the centrifugal pump. Due to the interaction between impeller blades and flow being pumped and high interaction between the impeller blades with stationary part (e.g the volute tongue region) as mentioned earlier, it can be observed that two main dominated frequencies that have been generated at the range of frequency the dominated frequency in this range are associated with the shaft rotating frequency (Rf), the blade passing frequency (BPF) and their harmonics. Also, it can be seen that from this figure the first rotational frequency under design flow rate has occurred at 45.91Hz and its second, third, and fourth harmonics have occurred at 91.8, 137.7, and

183.6Hz respectively. Also, the first blades passing frequency is taking place at 229.58Hz, and its second harmonic has occurred at 459.16Hz. Furthermore, it can be noticed that there are some additional frequencies are generated due different sources such as the driving motor and the cooling fan that has been used in order to cool the pump motor.

Many researchers into pumps applications have used high vibration frequency range higher than 20kHz to predict and diagnose any faults and failures. In this current study, an attempt has been made to use and analyse low frequency ranges, less than 20kHz, for detecting cavitation within a centrifugal pump. The important reason behind using latter technique is to decrease the cost of the accelerometer sensor. The details of using this method in frequency domain analysis (FDA) under different range of flow rates are presented and discussed in the next section.

3.7. The analysis of vibration signals based on frequency domain under various flow rates

Several experimental measurements have been carried out to measure the vibration signal. To analyse further, frequency domain analysis has been carried out in studying the effect of the different measurements of the flow rates on the vibration amplitude. For this purpose, the three-dimensional figure has been used in this section. This figure allows comparing more than one vibration amplitude signal in frequency domain and hence it can be illustrated that from this figure how the vibration amplitude it changes within the centrifugal pump under various operation conditions. For this purpose, in order to study the effect and sensitivity of using different frequency ranges and also to analyse, detect and then diagnose the inception and development of cavitation within the centrifugal pump by using vibration signal in frequency domain, the range of broadband frequency is divided into four main parts to obtain an apparent conception concerning the dominant frequencies in the pump: the first part deals with a low range of broadband frequency starting from 0Hz to 1kHz. While, the second part deals with range of broadband frequency is starting from 1kHz to 2kHz, the third part is starting from 2kHz to 10kHz and final part from 10kHz to 15kHz as illustrated in the next section.

3.8. Predict the cavitation within a pump at frequency range from 0Hz to 2kHz

Fig. 11 depicts the three-dimensional figure of vibration signals in the frequency domain based on the different range of frequencies. The first one is at low range frequency from (a) 0Hz to 1kHz and the second one is at range of frequency between (b) 1kHz and 2kHz under various

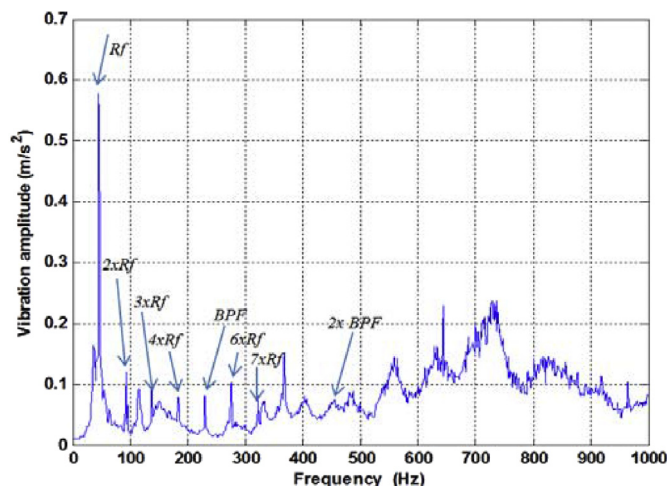


Fig. 10. Baseline frequency of vibration signal range from 0Hz to 1kHz at design flow rate at 2755rpm.

measurements of flow rates and the rotational impeller speed of 2755rpm. It can be seen that from both figures, there are small variances in the level of vibration amplitude within the centrifugal pump when the pump is operating less than 300 (l/min). However, it can be clearly observed that there is a significant increase in the level of vibration amplitude that occurred, when the pump is operated under flow rate higher than 350 (l/min). It can be noticed that this increase in the level of vibration amplitude occurs for both range frequencies from (0Hz to 1kHz) and (1kHz–2kHz) respectively. The reason behind that is due to the high interaction between water and the blades of the impeller, as well as the interaction between the impeller and volute. Moreover, one important reason is due to the occurrence of cavitation within the pump. Also from this figure, it is worth observing that under flow rate higher than 350 (l/min), the development of cavitation has already occurred. This is due to the smaller vapour bubbles generated in and around the impeller passages and hence, the bubbles impeding the flow rate being pumped. As a result, these bubbles cause increase in the level of vibration and noise inside the pump which then results in a decrease in performance of the pump. Therefore, a decrease in the pump performance is a reliable indication of cavitation has occurred in the pump. Also, the dominated frequencies for both frequency ranges are associated with the shaft rotating frequency (RF), blade passing frequency (BPF) and their harmonics. Furthermore, as mentioned in this section, it can be observed that the level of the vibrations was closely related to the occurrence of cavitation in the pump.

3.9. Predict the cavitation within a pump at frequency range from 2Hz to 15kHz

Fig. 12 depict the three-dimension vibration signal in frequency domain analysis (FDA) and the frequency range is from (a) 2Hz to10 kHz and (b) 10 Hz to 15kHz respectively, under various flow rates and the pump rotational speed of 2755rpm. It can be seen that these range of frequencies have the same trends as compared to previous figures for level of vibration amplitude in frequency domain under flow rate less than 350 (l/min). However, the trend of vibration amplitude increases with flow rate increases; it is also worth observing that the vibration amplitudes under high flow rates have much higher intensities as compares to the low flow rate due to the occurrence of the inception of cavitation at the flow rate lower than 350 (l/min). After the inception of cavitation has occurred, variations in the level of vibration amplitude increases as flow rate increases. When the cavitation increases continuously, it means the pump is operating under the conditions that cavitation has developed fully, leading to the level of increased amplitudes in the vibration signal, particularly under higher flow rate. Because of the occurrence of cavitation in the pump, bubbles begin to form and collapse within the pump which directly affect the level of the vibration amplitude. Furthermore, it can be observed that high-frequency range was more sensitive for detecting cavitation particularly at high flow rate as compared to low-frequency range.

It can be found that from above findings, the vibration amplitude when the pump works under inception and fully developed cavitation was higher than without cavitation condition (at the low flow rate) under the different range of frequencies as shown that in previous figures. The explanation for an increase in the level of vibration amplitude can be clearly noticed in the high flow rate, is due to the inception and development of cavitation process within a centrifugal pump at that time. Whereas, the occurrence of cavitation is due to decrease the inlet pressure at the eye of impeller under the water vapour pressure, causing the formation of bubbles in this region. During the decrease in the inlet pressure, these bubbles begins to grow in size due to the increasing flow rate that then leads to increase in the velocity of flow, which causes further decrease in the inlet pressure in this area. When cavitation start occurs, it increases the vapour bubbles thereby causing the level of vibration to increase due to the flow at inlet eye of an impeller becoming more turbulent. This is mostly due to the implosions of the bubbles

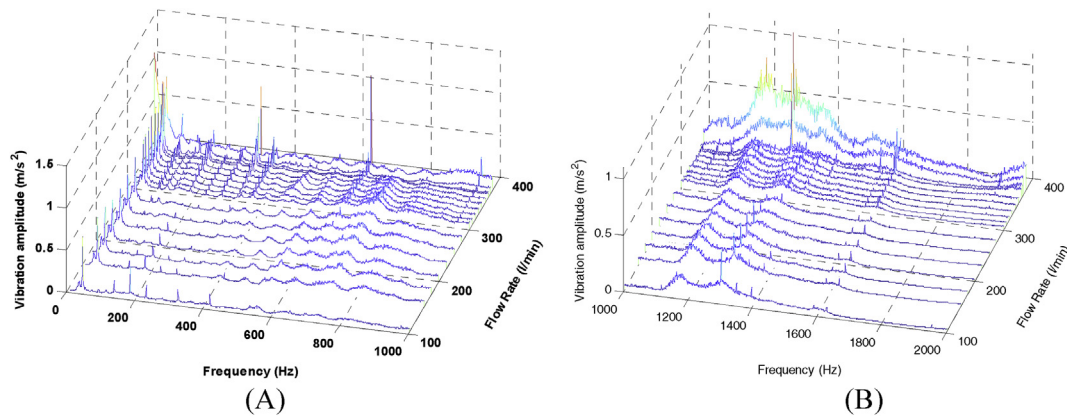


Fig. 11. A) Vibration amplitude under various flow rates and the vibration frequency range from 0 Hz to 1kHz, and B) 1kHz–2 kHz at 2755rpm.

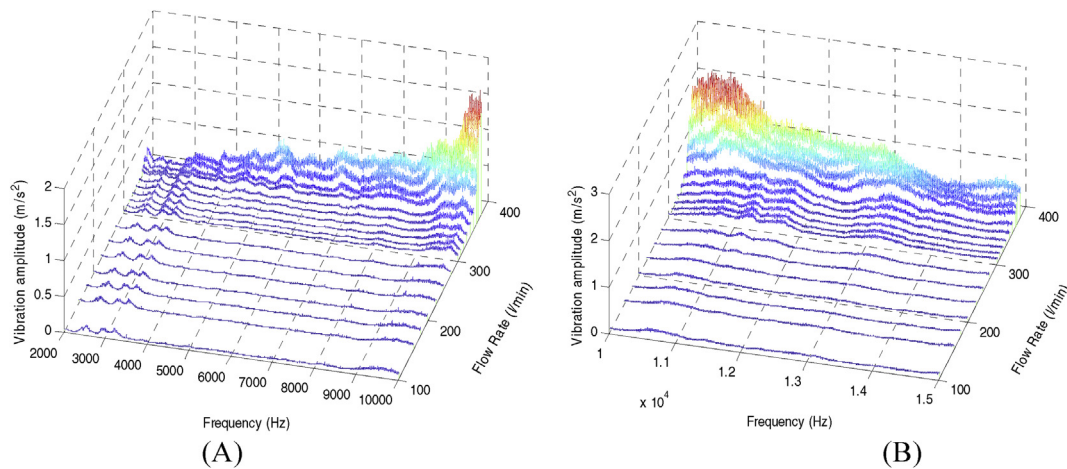


Fig. 12. A) Vibration amplitude under various flow rates and the vibration frequency range from 2kHz to 10kHz, and B) 10kHz to 15 kHz at 2755rpm.

surrounding the surface of the impeller. Furthermore, this process of collapsing and formation of bubbles could cause damage to the parts of pump particularly on the blades of impeller and hence, causes significant decrease in the performance of the pump. It can be seen that from above analysis the vibration amplitudes vary with the flow rates and different range of frequencies. Also, the above figures depict that the vibration amplitude for the range of frequency lies between (0–1.5 m/s^2), the range frequency 1–2kHz was (0–1 m/s^2), at high range frequency 2–10kHz was (0–2 m/s^2), and at range frequency 10–15kHz was (0–3 m/s^2). Hence, it can also be noticed that the vibration amplitude increases as the range of frequency also increases and these ranges of frequency vary according to the different flow rates. As a result, from the above finding, it can be concluded that when the flow rate increases, the vibration amplitude is increased. That has led in providing a good indication as to when cavitation occurs within the pump. The inception of cavitation occurred before flow rate of 350 (l/min) and it was fully developed when flow rate was higher than 350 (l/min). It was further noticed from the above figures that there are two dominant frequencies which are the rotation frequency (Rf) and blade passing frequency (BPF). From the peak of these frequencies and their harmonics, they can provide an alternative indication as to the occurrence of cavitation.

It can be seen that from above figures the range of frequency 10kHz–15kHz was more sensitive to detect the cavitation within a centrifugal pump as compared to the other range of frequencies. However, it can be observed that the range of frequency 1kHz–2kHz was as sensitive to detect the cavitation. The results have shown that the vibration, within a centrifugal pump are due to the occurrence of cavitation phenomenon that characteristically causes increase in the level of vibration amplitude,

which can be noticed under the different range of frequencies between 0 to 15kHz. Also, the results have shown that the use of FFT technique for signal processing in frequency domain to detect cavitation within a centrifugal pump was effective technique.

3.10. Analysis of vibration amplitude in frequency domain using different statistical features

As shown in the previous section, 3-D figures are used in order to analyse the level of vibration amplitude based on different range of frequencies. It can provide more knowledge regarding the inception and development of cavitation in the pump. However, during this experimental work, analysis of the vibration signal based on the frequency domain also helps to detect cavitation within a pump. Moreover, comparing the vibration amplitude under various operation conditions helps to match the variations in the level of vibration amplitude with the different characteristics of cavitation of the pump. This section has analysed the vibration amplitude signal in frequency domain, by using different statistical features such as mean and RMS vibration amplitude values. Furthermore, the analyses of these features are performed using MATLAB code. In this section, in order to obtain more details regarding the analysis of vibration signal, different range of broadband frequencies have been used due to the accelerometer sensor having also, a wide range of frequency band and hence, can be used to measure the different range of frequencies in the centrifugal pump. For comparison purpose in this study, the vibration under different range of frequencies will be analysed and discussed during the investigation in order to find the sensitive range of frequency to detect the occurrence of cavitation within a pump.

3.11. Analysis of vibration frequency using mean vibration amplitude value

Fig. 13 depicts the analysis of vibration signal using mean vibration amplitude value for various range of frequencies namely (0Hz–1kHz), (1kHz–2kHz), (2kHz–10kHz), and (10kHz–15kHz) respectively under operation conditions including flow rate as summarised in Table, and pump rotation speed of 2755rpm. The same trend can be seen in the vibration amplitude under both low and high range of frequencies. The minimum vibration amplitude for the low flow rate is less than the design flow rate of 300 (l/min), and no significant change in the level of vibration amplitude at this operation conditions. However, the results have showed that a rapid increase in the level of vibration amplitude for the high flow rate which is higher than design flow rate in excess of 350 (l/min). It then means that this increase signifies that cavitation has occurred and has starts to increase within the pump which was due to the fact that NPSHr was higher when compared to the NPSHa. These results show a strong agreement with the result obtained from the previous section. It can therefore be concluded that the level of vibration amplitude provides a good indication to predict and diagnose cavitation in the pump. Moreover, it was further noticed from above analysis of the level of vibration amplitude that the result is not limited to any particular range of broadband frequencies. However, it can be achieved through the use of various ranges of broadband frequency.

3.12. Analysis of vibration frequency using RMS vibration amplitude value

For further analysis of the vibration signal in frequency domain, Fig. 14 depicts the analysis of vibration signal using RMS vibration amplitude value for different range of broadband frequencies namely (0Hz–1kHz), (1kHz–2kHz), (2kHz–10kHz), and (10kHz–15kHz) respectively, under operation conditions including different flow rates as shown in Table and pump rotation speed of 2755rpm. It can be clearly seen that

the RMS value has the same trend of the vibration amplitude in the mean value, but different values of the vibration amplitudes. During the experimental measurements, it can be seen that there is no significant change in the vibration amplitude between 100 and 300 (l/min). But the vibration amplitudes are rapidly increased at the high flow rate higher than 350 (l/min). That means at this point, the pump operated under cavitation conditions due to NPSHr being higher than NPSHa.

It can be observed that from above results the use of statistical features such as mean and RMS values to analyse the vibration signal in frequency domain can provide more information regarding the prediction of cavitation within a centrifugal pump. Furthermore, during the experimental investigation in this study, it has been observed that the low range frequency between 0Hz to 2kHz is sensitive to predict the cavitation. Therefore, from above result it can be concluded that the analysis of vibration signal based on different ranges of broadband frequencies from 0Hz to 15kHz are efficient in order to predict cavitation particularly at the range of broadband frequency between 1 and 2kHz. At frequency range of 1–2kHz, there is no significant change when the pump is operating below 350 (l/min) as shown in the figure, and the maximum RMS value was 0.088 m/s^2 at around 152 (l/min). However, after 350 (l/min), the RMS value increases to 0.113 m/s^2 at 365 (l/min) meaning that the percentage increase for the RMS was 21.45%. Moreover, this increases in the level of vibration signal was due to interaction between the impeller and volute and also due to the occurrence of cavitation in the pump as mentioned earlier. As a result, an accelerometer sensor with low range of frequency can provide a good indication to predict and diagnose cavitation in the pump and hence, leads to decrease in the cost of sensor, as compared to using an accelerometer with high range of frequency. Furthermore, the analysis of variation in the levels of vibration amplitude within a centrifugal pump under different experimental measurements of flow rate in frequency domain analysis (FDA) under different range of frequencies were agreed with characteristics of cavitation that has been presented using NPSH curve. Based on the above findings, it can be seen

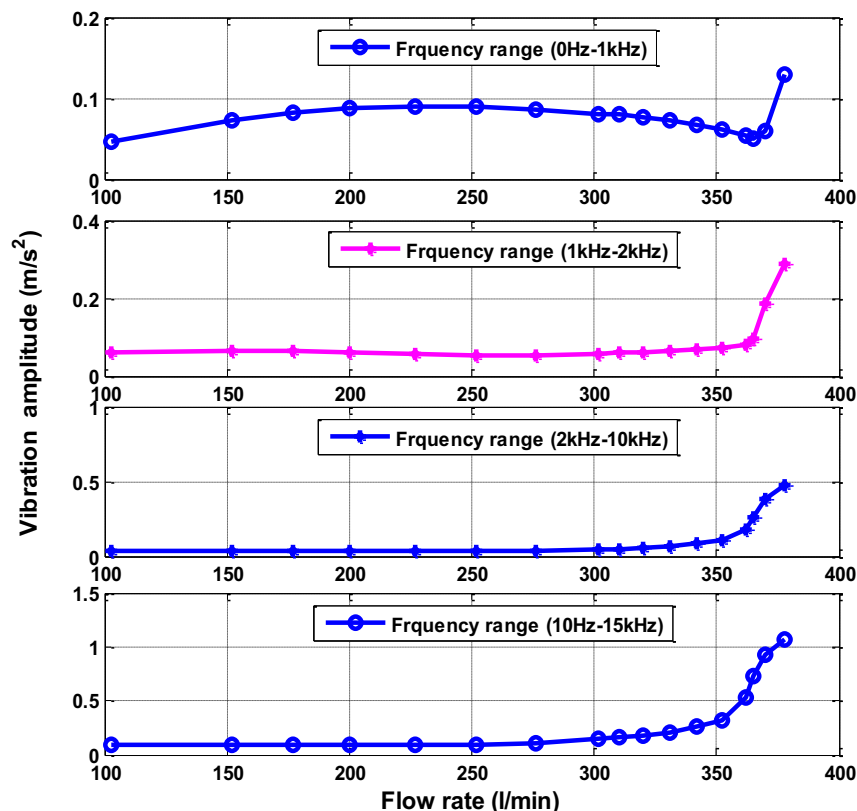


Fig. 13. Mean vibration amplitude value of the frequency range from 0Hz to 15 kHz at 2755rpm.

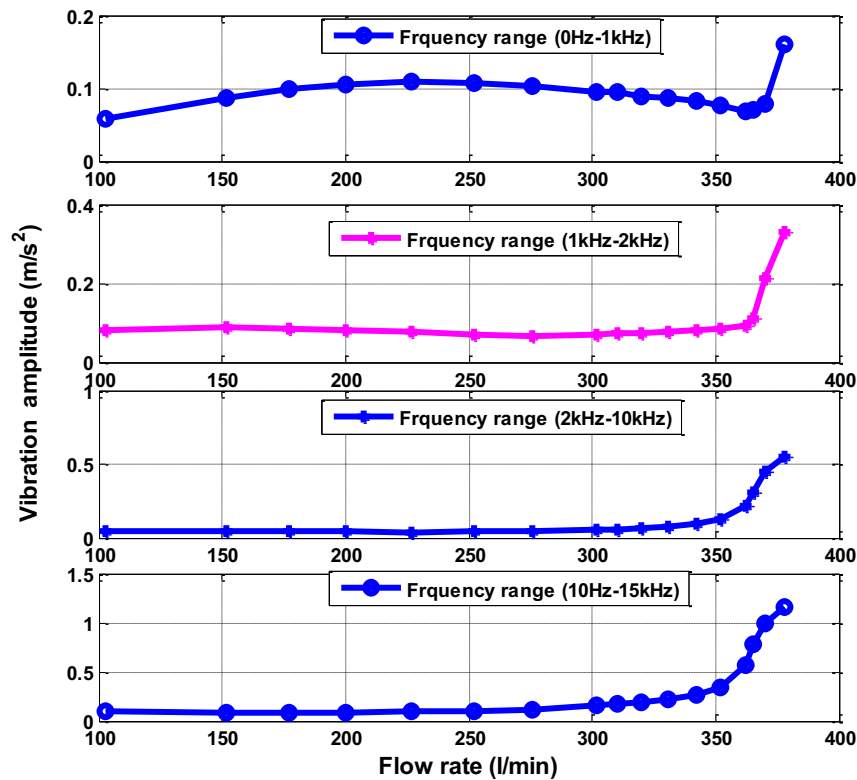


Fig. 14. RMS vibration amplitude value at frequency range from 0Hz to15 kHz at 2755rpm.

that when cavitation occurs in the pump, the level of vibration increases. This happens because of the formation and growth of the vapour bubbles within the impeller channels. Moreover, when these bubbles move and reach the higher-pressure region in the pump, they start to rapidly collapse, causing more unstable flow and then also cause increase in pressure fluctuations within the pump which then leads to increase in the level of vibration. Also, the above investigations have shown that the analysis of the vibration amplitude signals using different statistical features in frequency domain, have approximately the same trend as compared to the characteristics of cavitation that has been presented using the NPSHr. Therefore, for further quantifying of the vibration

signal in frequency domain analysis (FDA), Tables 3 and 4 summarise the mean and RMS vibration amplitudes values under different levels of cavitation conditions at different flow rates, pump rotational speed of 2755rpm and for different frequency ranges. It is evident that the values of all above statistical features of the vibration signal are increased as the level of cavitation increases. That is due to when cavitation occurs in the pump, and it will increase particularly at a high flow rate, causing more unstable flow which then increases the level of vibration. Furthermore, it can be concluded that the level of vibration and severity of cavitation within a pump is directly related to the pump flow rate.

Generally, after the investigation and discussion conducted

Table 3

Mean vibration amplitude value under different levels of cavitation conditions at different flow rates and pump rotational speed of 2755rpm.

Severity of cavitation	Flow rate (l/min)	Mean value	Mean value	Mean value	Mean value
		0Hz-1kHz (m/s ²)	1kHz-2kHz (m/s ²)	2kHz-10kHz (m/s ²)	10kHz-15kHz (m/s ²)
No Cavitation	103	0.0471	0.0609	0.0343	0.0904
Inception of cavitation	331	0.0719	0.0635	0.0652	0.2097
Development of cavitation	352	0.0619	0.0725	0.1065	0.3235
Fully Development of cavitation	378	0.1284	0.288	0.4742	1.0666

Table 4

RMS vibration amplitude value under different levels of cavitation conditions at different flow rates and pump rotational speed of 2755rpm.

Severity of cavitation	Flow rate (l/min)	RMS value	RMS value	RMS value	RMS value
		0Hz-1kHz (m/s ²)	1kHz-2kHz (m/s ²)	2kHz-10kHz (m/s ²)	10kHz-15kHz (m/s ²)
No Cavitation	103	0.0578	0.0819	0.043	0.0944
Inception of cavitation	331	0.0866	0.0764	0.0783	0.2223
Development of cavitation	352	0.0766	0.0847	0.1309	0.3434
Fully Development of cavitation	378	0.1595	0.3318	0.5543	1.153

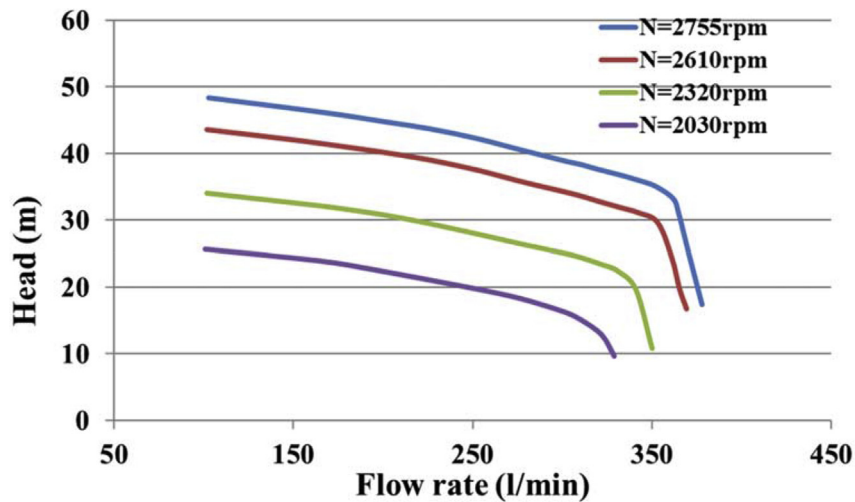


Fig. 15. Comparison between head of the centrifugal pump under different pump rotational speeds.

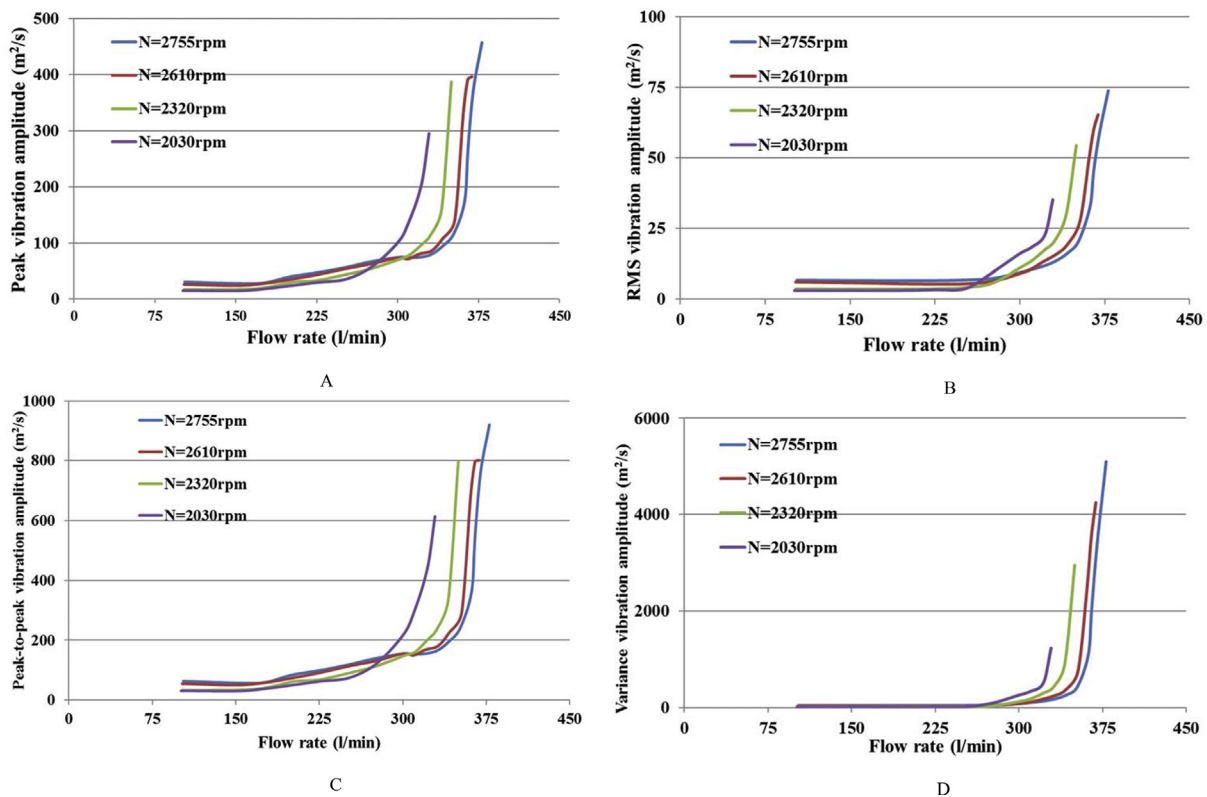


Fig. 16. Comparison between (A) peak, (B) RMS, (C) peak-to-peak, and (D) variance vibration amplitude values of the centrifugal pump under different pump rotational speeds.

concerning the performance and predict cavitation within a centrifugal pump under various flow rates. The details of the influences of different pump rotational speeds on the performance and predict cavitation conditions through the use of vibration technique in time and frequency domain are discussed and analysed in the following sections.

3.13. Effect of various pump rotational speeds to predict the cavitation within a centrifugal pump using vibration technique

As mentioned and clearly observed in the previous sections, the pump

performance depended directly on the different operating conditions. Therefore, the flow pattern behaviour distribution such as pressure and velocity, occurrence of cavitation as well as instabilities in the flow field within a centrifugal pump can all be predicted differently at various operational conditions. Hence, all of these parameters can affect the flow field, performance of the pump, and the detection of cavitation under various pump rotational speeds. Further analysis on the vibration signal for this research would be presented in order to predict the cavitation phenomenon within the centrifugal pump experimentally. The effect of various pump rotational speeds 2610, 2320, and 2030rpm respectively,

Table 5

Summary of the statistical features results of the maximum peak, RMS, peak-to-peak and variance values of the vibration amplitude under different pump rotational speeds.

Rotational speed	Peak	RMS	peak-to-peak	variance
(rpm)	(m/s ²)	(m/s ²)	(m/s ²)	(m/s ²)
2755	457.66	73.82	921.14	5099.6
2610	396.38	65.17	801.16	4249.5
2320	386.80	54.28	797.22	2947.6
2030	294.71	35.04	614.86	1227.0

corresponding to 0.9Nd, 0.8Nd, and 0.7Nd where Nd denotes the design rotational speed, and it is equal 2900rpm have been selected for the analysis purpose. The pump rotational speed has been precisely controlled by using the electronic inverter in the control panel. The range of pump capacity (flow rate) has been changed depend on the pump rotational speed. The next sections represent the results obtained from the experimental calculation of the pump under different pump rotational speeds.

For comparison purposes between the above cases, Fig. 15 depicts the head of the aforementioned cases under different pump rotational speeds. It can be observed that the head in the centrifugal pump follows a continuous downward trend with increasing flow rate at various rotational speeds under investigations. Also, it can be clearly seen that the head under N = 2755rpm is considerably higher than for the other three cases N = 2610 rpm, N = 2320rpm, and N = 2030rpm. The results have shown that the pump starts to operate under cavitation conditions at a flow rate higher than the design flow rate and then increases at a flow rate high than 350 (l/min). That means that when a pump operates at the high flow rate, it leads to decrease in the inlet suction pressure faster than at low flow rate and hence, cavitation will occur quicker. Furthermore, from the above findings, it can be concluded that the head of the centrifugal pump increases as the pump rotational speed also increases.

Table 6

Comparison between mean vibration amplitude values of the pump in frequency domain, under different rotational speeds at 0kHz–15kHz frequency range.

Rotational speed	Mean value 0Hz-1kHz	Mean value 1kHz-1kHz	Mean value 2kHz-10kHz	Mean value 10kHz-15kHz
(rpm)	(m/s ²)	(m/s ²)	(m/s ²)	(m/s ²)
2755	0.128	0.288	0.474	1.066
2610	0.075	0.243	0.444	0.995
2320	0.071	0.174	0.345	0.864
2030	0.041	0.113	0.176	0.558

Moreover, the pump rotational speeds are proportional to cavitation occurrence within the pump. That means when pump rotational speeds increases, occurrence of cavitation also increases due to the decreased pressure at the inlet eye of impeller which goes lower than the vapour pressure.

For comparison purposes between the above cases based on time domain analysis (TDA), Fig. 16 depicts the statistical features such as peak, RMS, peak-to- peak and variance values of the aforementioned cases under different pump rotational speeds. It can be seen that the maximum peak feature for N = 2755rpm is considerably higher than for the other three cases. For instance, for N = 2610 rpm, it is higher by 13.38%, for N = 2320rpm by 15.48%, and N = 2030rpm by 36.60%. Moreover, the maximum RMS value for N = 2755rpm is higher than the remaining three cases already listed by 11.72%, 29.98%, and 52.53% respectively. Furthermore, the highest peak-to- peak for N = 2610 rpm is higher than for the other cases by 13.025%, 13.45%, and 33.24% respectively and also the maximum variance value by 16.66%, 42.19%, and 75.93% respectively as given in Table 5. From the above findings, it can be concluded that the pump rotational speeds are proportional to the increase in the vibration amplitude. This means that when the pump rotational speed increases, the vibration amplitude also increases due to

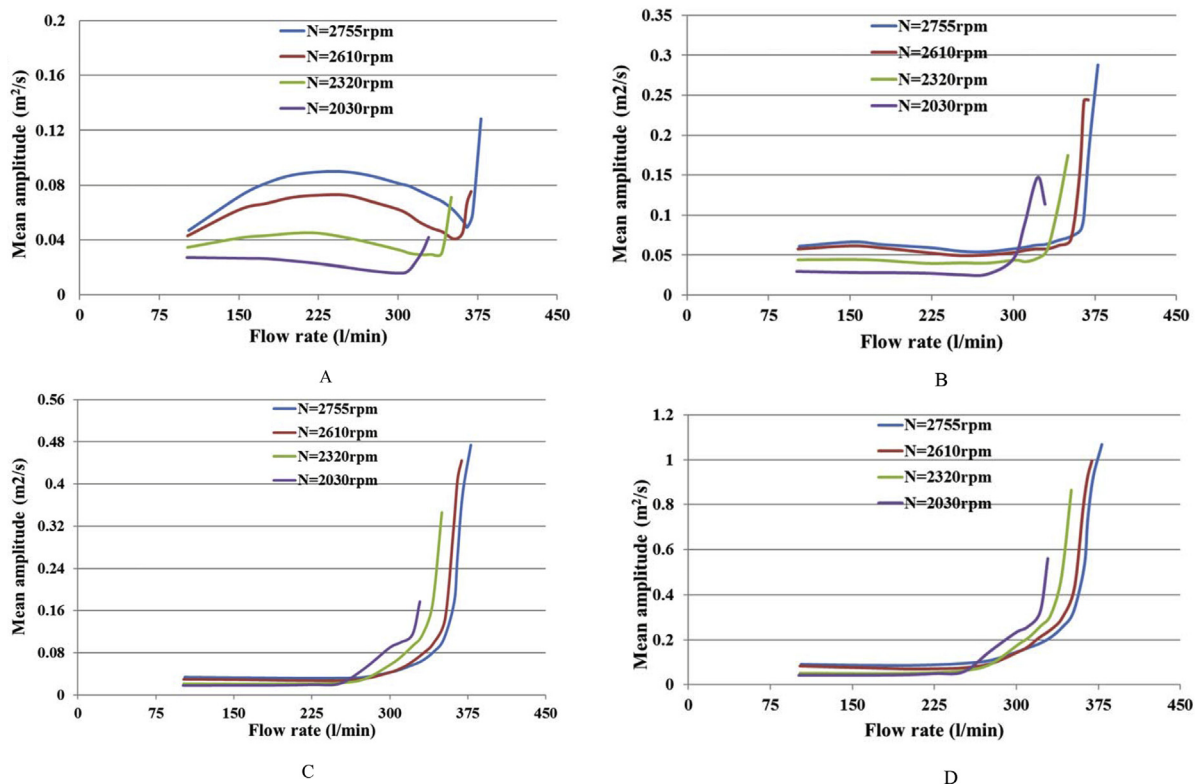


Fig. 17. Comparison between mean vibration amplitude values of the pump in frequency domain for different rotational speeds at range frequency (A) 0Hz-1kHz, (B) 1kHz-2kHz, (C) 2kHz-10kHz, and (D) 10kHz-15kHz under different pump rotational speeds.

the cavitation occurrence within a centrifugal pump. When vapour bubbles form due to cavitation for a long period of time, these bubbles collapse which causes drop in the performance of the pump and also damages some parts of the pump due to erosion on the surfaces of the pump. Furthermore, detection of the inception of cavitation at an earlier stage will help in prolonging the life of the pump and protecting the system from emergency shutdown.

Also, for comparison purposes between the above cases based on frequency domain analysis (FDA), Fig. 17 depicts the mean vibration amplitude values of the aforementioned cases under different pump rotational speeds and for the different range of frequencies which include 0Hz-1kHz, 1kHz-1kHz, 2kHz-10kHz, and 10kHz-15kHz. It can be clearly seen that the maximum mean feature under N = 2755rpm is considerably higher than for the other three cases as shown in Figure. Furthermore, the results from the frequency domain analysis have demonstrated that the mean vibration amplitude value for various ranged of frequencies can be used to predict different levels of cavitation within a centrifugal pump, especially at low range frequencies from 0Hz to 2kHz. However, it can be clearly seen that high ranges of frequency are more sensitive to predict cavitation as compared to the low range of frequency as shown in these figures.

Regarding the changes in vibration amplitude of the mean value for the centrifugal pump under different pump rotational speeds and various range of frequencies including 0Hz-1kHz, 1kHz-1kHz, 2kHz-10kHz, and 10kHz-15kHz, Table 6 provides more detailed comparison between all of the above cases under investigation. The values for the mean feature for N = 2755rpm, for different range of frequencies are considerably higher than for all three cases (N = 2610, N = 2320, and N = 2030rpm) as summarised in this table. It can be seen that the analysis on the vibration signals in frequency domain, using mean amplitude features, under different pump rotational speed shows that when the pump rotational speed increases, vibration amplitude also increases due to increases in

Table 7

Comparison between RMS vibration amplitude values of the pump in frequency domain under different rotational speeds at 0kHz-15kHz frequency range.

Rotational speed (rpm)	RMS value 0Hz-1kHz (m/s ²)	RMS value 1kHz-1kHz (m/s ²)	RMS value 2kHz-10kHz (m/s ²)	RMS value 10kHz-15kHz (m/s ²)
2755	0.1595	0.3318	0.5543	1.153
2610	0.1095	0.2855	0.5221	1.0789
2320	0.0926	0.1944	0.4111	0.9276
2030	0.0540	0.1762	0.2189	0.6055

the occurrence of cavitation within a pump under the different frequency ranges.

Furthermore, for comparison purposes between the above cases based on frequency domain analysis, Fig. 18 depicts the RMS statistical feature value for the aforementioned cases under different pump rotational speeds and for the different range of frequencies which include 0Hz-1kHz, 1kHz-1kHz, 2kHz-10kHz, and 10kHz-15kHz. It can be clearly seen that the maximum RMS feature for N = 2755rpm is considerably higher than for the other three cases. Also, the results from frequency domain analysis have demonstrated that RMS vibration amplitude value for various range of frequencies can be used to predict the cavitation within a centrifugal pump, especially at the low range frequency between 0Hz to 2kHz.

Furthermore, regarding the changes in vibration amplitude and trends of the RMS value for the centrifugal pump under different pump rotational speeds and for various range of frequencies which are 0Hz-1kHz, 1kHz-1kHz, 2kHz-10kHz, and 10kHz-15kHz, Table 7 provides these comparison between all the above cases under investigation. The values of RMS features for N = 2755rpm for different range of frequencies are considerably higher than for all three cases (N = 2610, N = 2320, and N = 2030rpm) as summarised in this table.

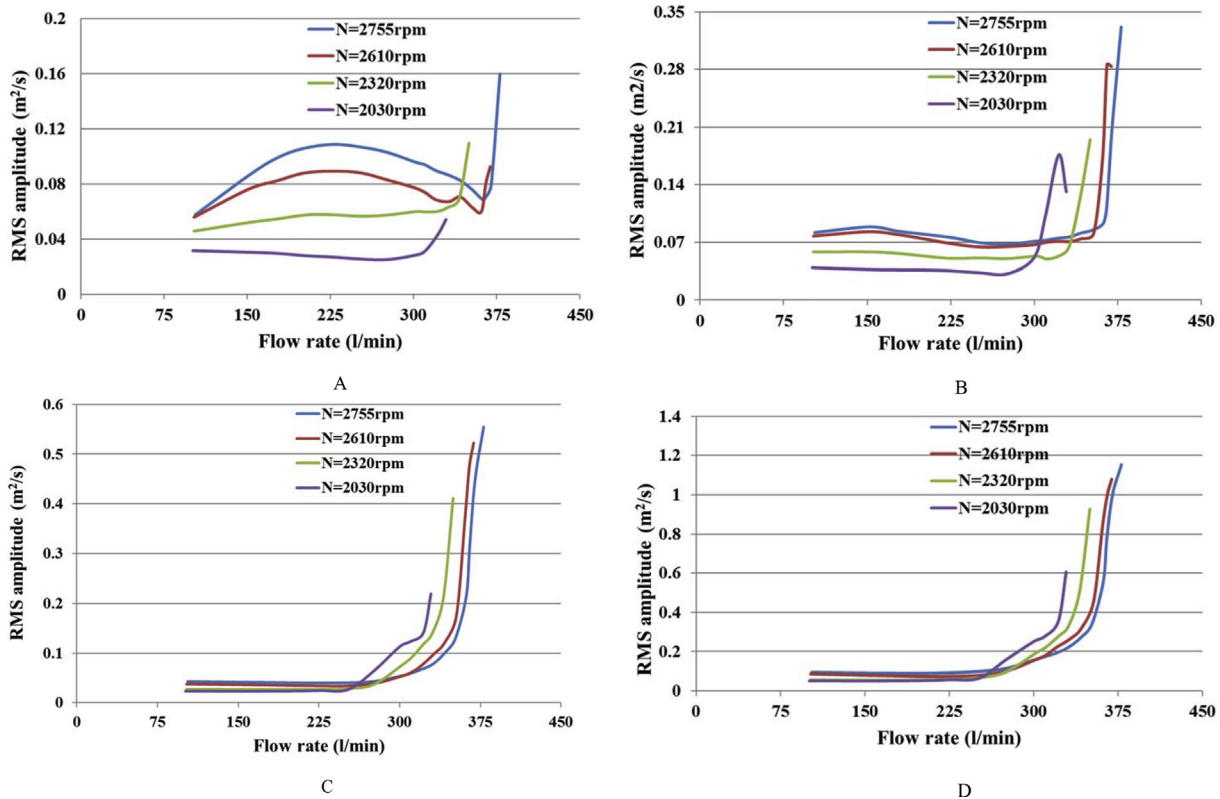


Fig. 18. Comparison between RMS vibration amplitude values of the pump in frequency domain for different rotational speeds at range frequency (A) 0Hz-1kHz, (B) 1kHz-2kHz, (C) 2kHz-10kHz, and (D) 10kHz-15kHz under different pump rotational speeds.

4. Conclusions

Based on above results in this section, several flowing conclusions have been drawn regarding the effect of different flow rates and pump rotational speeds on the vibration signal and performance of the centrifugal pump.

1. The trend for the head of the centrifugal pump gradually decreases when flow rate is increased due to the hydraulic and mechanical losses as well as different levels of cavitation occurrence within a pump
2. When the pump operates under low flow rate, no cavitation occurs due to NPSHa being higher than the NPSHr. But at flow rate greater than 350 (l/min), cavitation occurs in the pump
3. The results have shown that when the pump works under unstable flow rate, it leads to change in the dynamic characteristics within a centrifugal pump.
4. The level of cavitation within a centrifugal pump has been directly linked with the pump flow rate and pump rotational speed.
5. Under cavitation process, the vapour bubbles increase due to decrease of the fluid pressure, lower than the vapour pressure. Moreover, they have high effects on the flow within a pump.
6. The inception of cavitation process mostly occurred at the eye of the impeller around or closed to the impeller blades leading edges.
7. The vibration signal analysis in time domain, using different statistical features can be considered as a first indication to determine when cavitation has occurred in the pump.
8. The peak and peak-to-peak feature values were the most sensitive to detect cavitation within a pump when compared to RMS and variance features.
9. Frequency domain analysis technique to investigate the vibration amplitude has been a satisfactory technique to predict the inception and development of cavitation within a pump
10. The use of features such as mean and RMS vibration amplitude values to analyse the vibration signal in frequency domain provides more information regarding the prediction of cavitation within a centrifugal pump
11. The analysis of the variation in the level of vibration amplitude within a centrifugal pump, under different experimental flow rate measurements in time domain by using different statistical features and also in frequency domain under different ranges of frequencies was in agreement with the characteristics of cavitation that has been presented using the NPSH curve
12. During the course of further investigation in this study, it was found that from the analysis the vibration signal using mean and RMS amplitudes features, for the different broadband range of frequencies. The results have revealed that using low-frequency range between 1kHz and 2kHz was sensitive to predict cavitation in the pump. Therefore, it is possible to use an accelerometer that has low range of frequency which would decrease the cost of the sensor when compared high range of frequency sensor
13. Based on the above findings, the severity of cavitation can be gauged by increasing the level of vibration amplitude value. It provides a good indication regarding the occurrence of the severity of cavitation within a centrifugal pump

Declarations

Author contribution statement

Ahmed Ramadhan Al-Obaidi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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