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Spectrum Analysis of Vibration Signals for Cavitation Monitoring

*Salem. A. Al-Hashmi, Ahmed. B. Mohammed, Ibrahim Nasir and M. Elhaj
Department of Electronic and Electrical Engineering ,Faculty of Engineering & Technology, Sebha University, Libya
*Corresponding author: sal.mana@sebhau.edu.ly

Abstract: This paper reviews the sources of vibration from a centrifugal pump during normal operation and explains how these sources are excited by other factors, particularly the onset of cavitation. It discusses the efficacy of the vibration method for detecting and diagnostic the cavitation in centrifugal pumps, using spectrum analysis. Finally, the experimental results of using vibration method for monitoring cavitation in centrifugal pumps has been presented and discussed.

Keyword: Centrifugal pump; Cavitation; Vibration; Base line spectrum; Vane passing frequency; Broadband frequency.

مراقبة التكهف باستخدام تقنية التحليل الطيفى لاشارات الاهتزاز

*سالم الهاشمي و أحمد أبوسيف و إبراهيم السنوسي و محمد الحاج
قسم الهندسة الكهربائية والإلكترونية – كلية العلوم الهندسية والتقنية–جامعة سبها، ليبيا
*للمراسلة: sal.mana@sebhau.edu.ly

الملخص هذه الورقة تقدم مراجعة لمصادر الاهتزازات الميكانيكية الصادرة من المضخات السطحية اثناء التشغيل العادي وتشرح كيفية تأثر هذه المصادر بالعوامل التشغيلية الاخرى وخاصة بداية عملية التكهف، حيث أن هذه الورقة تناقش كفاءة تقنية استخدام إشارات الاهتزاز في عملية مراقبة وتشخيص التكهف في المضخات السطحية وذلك باستخدام التحليل الطيفي لهذه الإشارات المسجلة من المضخة. و أخيراً تمّ تقديم و مناقشة نتائج هذه التجربة التي أجريت من جل مراقبة التكهف في المضخات السطحية، حيث تشير النتائج الى امكانية استخدام طريقة التحليل الطيفي لإشارات الاهتزاز من أجل اكتشاف و تشخيص ظاهرة التكهف في المضخات السطحية.

الكلمات المفتاحية: مضخة طرد مركزي، التكهف، اهتزاز، طيف خط الأساس ، ريشة تمرير التردد، تردد النطاق العريض.

Introduction

The rotating machines such as pumps, compressors, fans...etc. are sending different signals such as acoustics and vibration; reflect its internal condition [1]. These signals are contained valuable information about its operation condition. Now a day, maintenance engineers are utilised these information as valuable strategy for the purpose of the rotating machines maintenance. Cavitation is simply the vaporization of fluid in the pump. It occurs when the net positive suction head available is less than the net positive suction head required. Technically, cavitation can be defined as the boiling of fluid at ambient temperature as a result of reduced pressure [2, 3]. The effects of cavitation in centrifugal pumps are: deterioration of the hydraulic performance, damaging pump's components, generates high vibration and noise. To prevent pumps from all these bad consequences, monitoring system must be adopted for detecting and diagnose cavitation at early stage [4, 5]. Results of several theoretical and experimental works have been published on the subject of cavitation detection in centrifugal pumps using vibration methods [6, 7, 8]. Most of these publications consider the analysis of vibration signals in frequency domain, specially the information in high frequency range above 20 kHz. Works [6, 7] show that the discrete frequency tone at half blade passing frequency (HBPF) could be used as an indicator of developing cavitation in a centrifugal pump. The rest of the paper presents pumping system test-rig configuration, signal analysis, work results and conclusions of this work.

The sources of pump vibration

The sources of vibration in centrifugal pumps can be categorized into three types: Mechanical causes, Hydraulic causes & Peripheral causes.

1- Mechanical Causes of Vibrations

The mechanical causes of vibrations include:

- ✓ Pump and driver misalignment
- ✓ Unbalanced rotating components,
- ✓ Bent or warped shaft
- ✓ Damaged impellers and non-concentric shaft sleeves
- ✓ Inadequacy of foundations or poorly designed foundations
- ✓ Pipe strain (either by design or as a result of thermal growth),
- ✓ Worn or loose bearings, Loose parts,
- ✓ Thermal growth of various components, especially shafts
- ✓ Loosely held holding down bolts
- ✓ Rubbing parts
- ✓ Damaged parts.

2- Hydraulic Causes of Vibrations

The hydraulic causes of vibrations include:

- ✓ Impeller vane running too close to the pump cutwater
- ✓ Operating pump at other than best efficiency point (BEP)

- ✓ Internal recirculation
- ✓ Vaporization of the product
- ✓ Turbulence in the system (non aminar flow),
- ✓ Air entrapment into the system through vortex etc.
- ✓ Water hammer.

3-Peripheral Causes of Vibrations

The peripheral causes of vibrations include:

- ✓ Harmonic vibration from nearby equipment or drivers.
- ✓ Operating the pump at a critical speed
- ✓Temporary seizing of seal faces (this can occur if you are pumping a non-lubricating fluid, a gas or a dry solid, a pump discharge recirculation line aimed at the seal faces.)

Pump vibration caused by Cavitation

Cavitation is one source of vibration sources in centrifugal pumps. Different sizes of Bubbles due to cavitation appear and collapse randomly, therefore produce turbulent energy (vibration and noise) either in broadband frequency or at a discrete frequency. A broadband frequency (1 - 20 KHz), which is pronounced with discrete frequency components, is the characteristic of the vibration signal acquired from centrifugal pump under cavitation [6, 7]. The broadband vibration frequency may come from localised pressure fluctuations which involve a number of different mechanisms such as cavitation implosion, turbulence, flow friction, high flow velocities, internal recirculation and water hammer [1, 10]. In general, higher flow-rate operations are likely to create more cavitation, turbulence, velocity influences and friction while lower flow-rates may have more internal recirculation. These variations, in turn, cause more pressure variation and hence, higher vibration and noise [10, 11, 12]. The interaction between the flowing fluid and the moving parts such as rotor and cooling fan blades or the interaction of the rotating rotor vanes with the nearby stationary parts such as the cutwater and casing produces the discrete frequencies [7]

Many investigations on a wide range of hydraulic machinery have shown that vibration levels increase when a turbo machine works under cavitation. The nature of cavitation is chaotic and thus, forms a part of turbulent vibration and noise. There are two types of hydrodynamic processes inducing cavitation vibration. One type is because of low flow rate and internal recirculation of local flow causing the formation of stalls with high velocities at their core and a significant lowering of the static pressure at that location [11, 12]. Insufficient suction head of pump produces the other type of cavitation vibration. This type of cavitation causes instability in pressure and mass flow throughout the entire pump and it is known as auto-oscillation. Cavitation can be quite destructive to internal pump components if left uncorrected. It is often responsible for the erosion of impeller.

I. TES_RIG CONFIGURATION

A single suction, single stage, single volute, end suction / top discharge, centrifugal pump has been used for this experimental work. This pump has a 5-blade closed-face impeller and is driven directly by a 4 KW three-phase induction motor. The technical specifications of the pump are summarised in Table (1). Figure (1) shows the arrangement of the test-rig. To simulate different operational conditions, throttling valves were installed at both the suction and discharge sides. According to ISO 3555, the predicted characteristics between the Net Positive Suction Head Available (NPSHA) and Net Positive Suction Head Required (NPSHR) are depicted in Figure 2 for this system, it is seen that the cavitation will start when the flow rate is larger than 340 l/min where the NPSHR is higher than the NPSHA. Based on these characteristics, therefore, the cavitation can be simulated by adjusting the flow rate and thus allowing the investigation of acoustic signals

Table 1: technical specification of the test rig pump

1	Suction diameter	0.0508 (m)
2	Discharge diameter	0.01375 (m)
3	Number of blades	5
4	Number of fan blades	12
5	Rotational speed	2800 rpm
6	Flow rate	300 l/min
7	Total head	38 m
8	Number of poles	2 pole
9	Supply voltage	415 volt
10	Supply power	4 kW

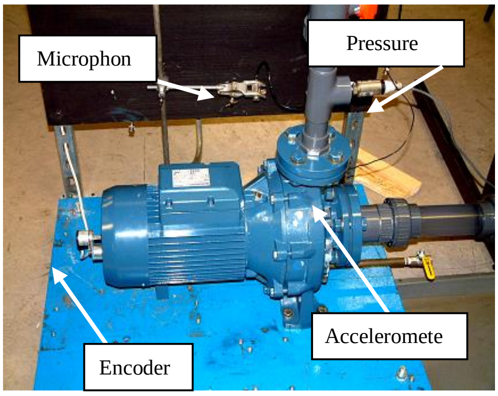

Fig. 1 Test-Rig configuration

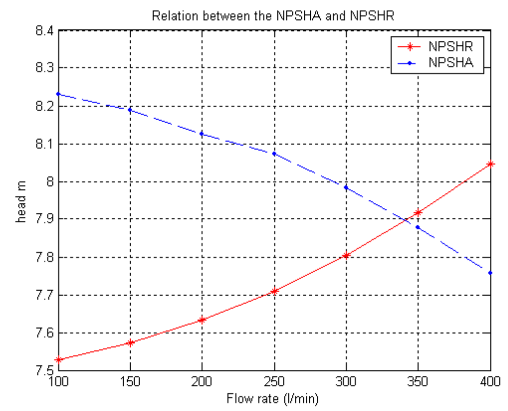

Fig. 2 The relation between NPSHA&NPSHR

Considering cost effectiveness of cavitation detection in practice, only single channel vibration was measured. The vibration signal is acquired by using anaccelomete.The sensor was placed on the pump casing. In this work DAQ card model PD2MF1650 has been used as analog to digital converter (ADC). The resolution of this (ADC) is 16 bits and sampling frequency which used for the measurement is 62.5 KHz. The change inflow rate was achieved by throttling the discharge valves while the speed of the pump was maintained at 2950 rev/min. vibration signals were collected at six different flow rate values: 200, 250, 300, 350,380 and 400 l/min. Each test has been repeated three times. It is important to mention that all analysis was done offline. From Figure 2, it can be seen that the pump cavitation starts at the flow rate equal to 340 l/min and becomes more severe as the flow rate exceeds 340 l/min. Thus, these flow rate settings allow for the study of the pump vibration at different severity of cavitation.

II. SIGNAL ANALYSIS

In general, vibration signals are random in nature and can be either stationary or non-stationary. Random time functions can be assumed as stationary signals at a specific point in the future. It is acceptable to assume that the time average for one time record is the same for all time records.

As raw data is noisy in nature, hence it is difficult to use these signals directly for cavitation detection and diagnostic. Therefore, the signals are processed and analysed in frequency domain to find optimal detection features. Baseline spectrum, waterfall, andmean values were used to find useful parameters for cavitation detection.

A. Frequency Based Analysis of vibration signal

1) Baseline Spectrum Analysis

As explained in [15], the vibration method depends strongly on spectrum based analysis; the acquisition, saving and analysis of data sets from healthy machines in the frequency domain is the first step in establishing a predictive maintenance strategy. The baseline spectrum is used as a reference for all future measurements. It is important to identify all the frequencies in the baseline spectrum and correlate carefully each frequency to the pump operation.

Figures 3 and 4 show the vibration spectrum.This spectrum has been produced based on acquired signal from the pump at normal speed 2900 rpm and at its designed flow rate 250 l/min. range. Therefore, it can be considered as a healthy spectrum or simply a baseline spectrum. In order to get a clear idea about the dominant frequencies, the spectrum is divided into two parts: a low frequency part (from 20Hz to 1 kHz) and a high frequency part (from 2 kHz to 20 kHz).

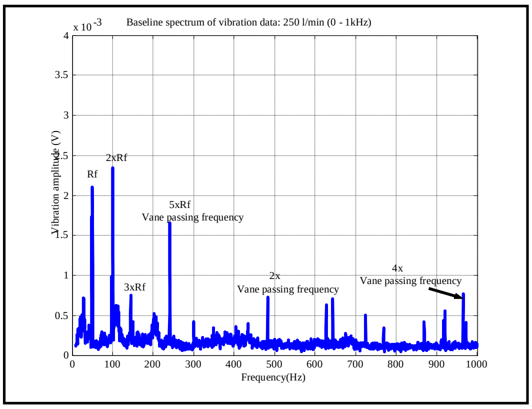

Fig. 3 Baseline spectrum (0 – 1 kHz)

As can be seen from figure (3), the discrete frequency components dominate the low vibration spectrum. These frequencies include rotating shaft frequency (RF), vane-passing frequency (VPF) and their harmonics. The main distinct frequency in the low frequency spectrum are the shaft rotational frequency (48.3 Hz), second harmonic and fifth harmonic which is the vane passing frequency VPF (241.5 Hz), motor cooling fan (580 Hz) and their higher order harmonics. These frequencies originate from pump operation i.e. the interaction between the mechanical and flow processes and confirms the theory of the vibration mechanism explained earlier in this paper. The vibration spectrum includes several frequencies with high amplitudes, with the highest peak at 880 Hz. These components may be from the motor operation. Table 2 surmise these frequencies and potential sources. The high frequency spectrum (2 kHz – 20 kHz) of the vibration, shown in figure (4), displays the typical features of broadband frequency. As can be observed the high frequency spectrum is dominated by a broadband frequency (2 – 20 kHz), however it also contains a few discrete frequencies. As explained above, this feature is due to the motion of the liquid and the natural operation of the centrifugal pump [16]. This spectrum includes a discrete frequency equal to 2.63 kHz and its harmonics. Although the amplitude of these components is high, they do not change with pump load and, therefore, can be attributed to system resonance.

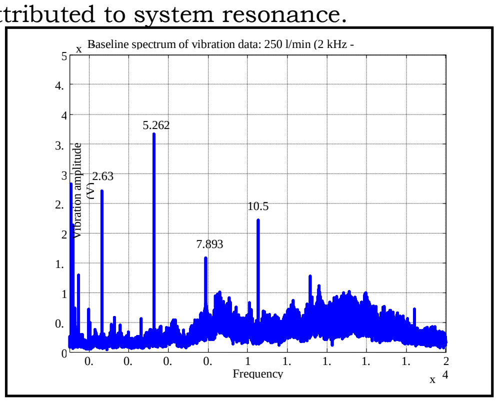

Fig. 4 Baseline spectrum (2 – 20 kHz)

The vibration spectrum does not have a high amplitude at half vane-passing frequency (VPF), which was used in other research as the primary means of cavitation detection in a centrifugal pump. The fact that amplitude information at half of the VPF is not a suitable cavitation indicator in this instance may be accounted for the use of a different pump in this study from that pump which used in previous research. Since the vibration method depends strongly on spectrum based analysis; the acquiring, saving and analysis of data sets from healthy machines in the frequency domain is the first step in establishing a predictive maintenance program [15]. All the frequencies in the baseline should be identified and their behavior examined in different conditions. This process should be done when the machine is first installed or after the first scheduled maintenance. These data sets can be used as a reference data set for all future measurements.

2) Spectrum analysis

Figures (5) and (6) present the spectrum of vibration signals at specified flow rates. In order to compare vibration spectrums at different flow rates, a three-dimensional or waterfall plot was used. The three-dimensional plot enables comparison of more than one spectrum to another and makes it possible to discover which amplitude frequencies do not change with the pump operation (resonance frequency). Figures 5 and 6 show the waterfall plots of the low and high frequency parts of the vibration spectrum, respectively. As seen from these figures, at a flow rate of less than 350 l/min, the level of pump vibration was fairly constant. A significant increase in the vibration level (at broadband frequency morethan 1 kHz) is observed, when the flow rate exceeds 350 l/min. This increase in the pump vibration level at low and high frequency range concurs with the characteristics of cavitation presented in figure 2.

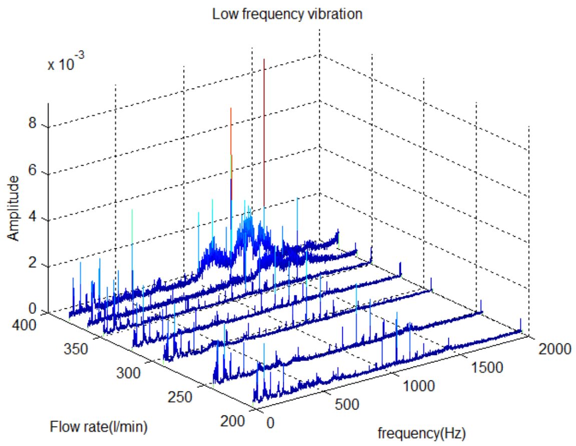

Fig. 5 Waterfall plot of acoustics data (20 Hz – 2kHz)

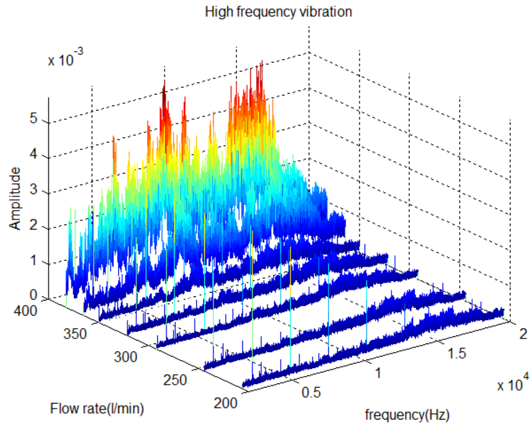

Fig. 6 Waterfall plot of acoustics data (2 – 20 kHz)

4-Mean Value Analysis

Previous research into this field has made use of a half vane-passing frequency and broadband frequency range for detection and diagnosing cavitation in centrifugal pump [5,6]. In this study, frequency ranges of less than 1 kHz were used in addition to broadband, in order to reduce computation requirements and to reduce the price of the sensor required. The relation between mean value of vibration spectra and the pump flow rates are presented in figure (7) the upper plot of the figure illustrates the low frequency amplitude, while the lower plot shows the high frequency amplitude. As can be seen from the upper plot of the vibration frequency, minimum levels are around the rated The result confirms the analysis presented in sections 3. At flow rates upto 345 l/min, the mean value of the high frequency spectrum is minimal and nearly constant and at flow rate greater than 345 l/min, a significant increase in vibration level is observed. From this, it can be concluded that vibration amplitude can be used as the threshold for the detection of the onset of cavitation. The amplitude above this threshold indicates the severity of cavitation.

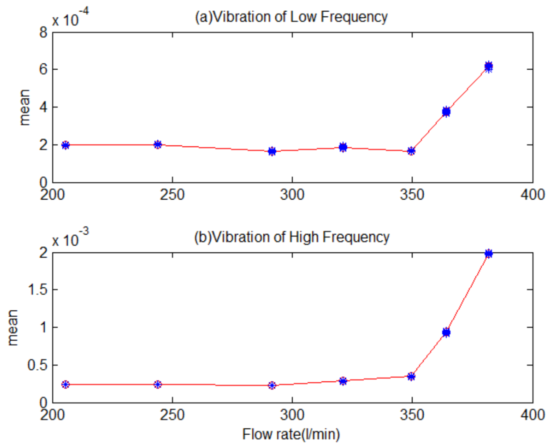

Fig. 7 Mean value of acoustics spectrum.

The analysis of the mean value of the vibration spectrum includes different frequency ranges. Analyzing different frequency range of the vibration spectrum shows that above result is not restricted to some specific frequency range, but can be obtained by using different ranges of frequency (0-19 kHz).

The relation of the mean value of the vibration at frequency ranges 1-4 KHz and 4-7 KHz is presented in []. These figures indicate that all the frequency ranges give the same result as the broadband frequency range. Therefore, the cavitation in centrifugal pump can be detected using relatively cheap vibration sensors. As explained above, the strength of vibration of a pump in normal conditions and under cavitation depends on many factors. These factors include type, size and condition of the pump. Thus, it is not possible to apply the threshold obtained in this study, which is used for cavitation detection and diagnosis in test-rig pump to other type of pumps unless applied this method on many different pumps. Normalising the mean value of the pump vibration in the high frequency band with the amplitude averaged over the whole frequency band of interest can be good way to generalise the threshold for other pumps.

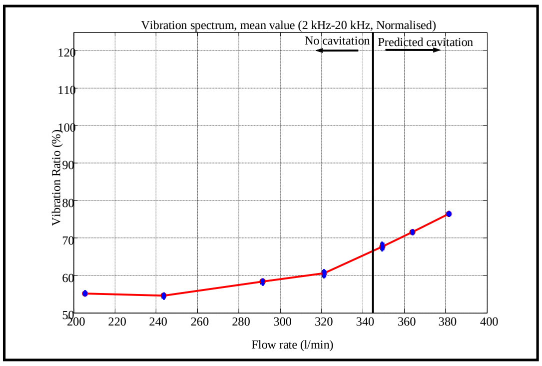

Fig. 8 Trend of vibration amplitude (normalised).

Figure (8) shows the trend normalized mean value of the pump vibration with flow rate. The figure represents the high frequency range of the vibration spectrum. As seen in the figure, cavitation inception can be detected at the 60% of the pump vibration ratio. Therefore, the level of 60% of the pump vibration can be used as threshold for cavitation inception and any increase in the threshold indicates the severity of cavitation.

CONCLUSIONS

The study confirmed previous studies, which indicates that broadband vibration frequency (2kHz – 20kHz) of the test-rig pump is significantly excited by the presence of cavitation. In the same time, the study concludes that all frequencies in the low frequency range (0 – 1 kHz) of the vibration spectrum can also be used for detecting cavitation in a centrifugal pump, therefore, using of low frequency vibration sensor (0- 1 kHz) is enough for cavitation detection. Since low frequency sensors are cheaper in comparison to high frequency sensors and therefore, the use of low frequency range (0 – 1 kHz) for cavitation monitoring in a pump reduces the costs of the vibration sensors hence the cost of condition monitoring system. The rotational and vane-passing frequencies change with the change in pump flow. However, the change of these frequencies, reflects only the pump operation and the study does not find any clear trend in theses frequencies with connection to cavitation process, therefore, these frequencies cannot be used as a cavitation indicator in a centrifugal pump.

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