Journal of Applied Fluid Mechanics, Vol. 12, No. 6, pp. 2057-2067, 2019.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.29252/jafm.12.06.29901

An Experimental Study on Vibration Signatures for Detecting Incipient Cavitation in Centrifugal Pumps Based on Envelope Spectrum Analysis

A. R. Al-Obaidi[1] and H. Towsyfyan[2†]

[1] *Department of Mechanical Engineering, Faculty of Engineering, Mustansiriyah University, Baghdad, Iraq*
[2] *Institute of Sound and Vibration Research (ISVR), Digital Signal Processing and Control Group, University of Southampton, SO17 1BJ, UK*

†*Corresponding Author Email: ahmedram@uomustansiriyah.edu.iq*

(Received December 9, 2018; accepted February 10, 2019)

ABSTRACT

Vibration signatures have been studied for monitoring the condition of centrifugal pumps by many researchers, however, there is limited published information on the application of vibration analysis to incipient pump cavitation. The paper will review the state of the art in the field and develops an effective signal processing approach based on envelope spectral analysis to close this gap. A purpose-built test rig was employed for recording vibration signals from a centrifugal pump at a wide range of operating conditions. The collected data was then processed using time domain and frequency domain analysis methods. The study has shown that the vibration energy concentrated mainly in the frequency range between 8-15 kHz. At the flow rates less than 300(l/min), i.e. in design flow rate range, the vibration amplitudes remain constant and does not show a notable change by the flow rate increase. However, a notable increase in the vibration level is evident when the flow rate exceeds 300 (l/min). Analysis the result of filtered vibration signatures has revealed that vibration signal parameters: peak value, root mean squared (RMS), crest factor along with vibration spectrum allow development of cavitation (for the flow rates higher than 300 (l/min)) to be diagnosed reliably. However, conventional signal processing methods may not produce a clear separation of the incipient cavitation from the healthy baseline. Therefore, envelope spectrum analysis has been carried out on recorded vibration signatures to detect the onset of cavitation from the baseline and satisfactory results have been perceived.

Keywords: Centrifugal pump; Inception of cavitation; Vibration signal; Envelope spectrum analysis.

NOMENCLATURE

D_1	suction pipe diameter	(n)	Discrete domain sequences
D_2	discharge pipe diameter	PV	Cauchy principle value
f	Darcy friction factor	Q	flow rate
g	acceleration of gravity	*RMS*	Root Mean Square
H_{tout}	total head at the inlet of the pump	(t)	Hilbert transform of signal
H_{tin}	total head at the outlet of the pump	V_1	water velocity in suction pipe
H_f	friction head	V_2	water velocity in discharge pipe
H_S	static suction head	$X(t)$	time domain signal
H_t	total head in the centrifugal pump	$X(\varpi)$	Fourier transform of signal
$H(\varpi)$	transfer function of the discrete Hilbert transform	$\bar{X}(\varpi)$	the Fourier transform of the Hilbert transform
$h(n)$	discrete Hilbert transform	Z1	suction elevation of the pump
L	pipe length	Z2	discharge elevation of the pump
NPSH	Net Positive Suction Head		
NPSHA	Net Positive Suction Head Available	ρ	fluid density
NPSHR	Net Positive Suction Head Required		

1 INTRODUCTION

A recently published review of Processes (Stan *et al.*, 2018) reiterated the important role of centrifugal pumps (Karassik and Gulich, 2008) in the industry, especially in the gas and oil sector for fluid transport. According to statistics, among various type of pumps, the use of centrifugal pumps in the market of industrially advanced countries reaches about 64% (Al Thobiani, 2011). Since centrifugal pumps are often located on a critical path of the production line, their unexpected sudden failure causes direct losses, e.g. stop the local production process in the oil and gas industry, as well as indirect losses, e.g. maintenance cost, (Al Thobiani, 2011 and Kamiel, 2015) in critical industrial applications. Centrifugal pumps may fail due to several problems e.g. lubrication failure, fatigue and cavitation. Details on major failure modes of centrifugal pumps can be found in (McKee *et al.*, 2001).

The latter, cavitation, is one of the most challenging flow instabilities inside centrifugal pumps leading to high levels of noise and vibration as well as a notable reduction in pump efficiency (Sánchez *et al.*, 2018 and Soni, 2018). Cavitation can cause erosion and pitting in impeller blades and finally unexpected failure of a pump either due to damaged impeller or faulty components (e.g. bearing or mechanical seal). A very good survey with focus on the effect of cavitation on centrifugal pumps can be found in (Binama *et al.*, 2016). To avoid premature failure of centrifugal pumps due to developed cavitation, different non-destructive testing (NDT) methods based upon vibration analysis (Al Thobiani, 2011 and Kamiel, 2015), noise emission (Chudina, 2003 and Čdina, 2003), acoustic emission (Alfayez *et al.*, 2005), ultrasonic testing (Yan *et al.*, 2015) and flow visualisation (Al-Arabi *et al.*, 2011) have been frequently investigated. Besides well-known NDT modalities, the successful application of recently developed methods such as load torque signature analysis (LTSA) (Stopa *et al.*, 2014), time-domain analysis of discharge pressure signal (Samanipour *et al.*, 2017) and capacitance signal analysis (Al Thobiani, 2011) have also been reported in the literature. However, these modalities may not be effectively used in industry due to their technical limitations. For instance, in flow visualisation the access to the region of cavitation is needed. Moreover, the technique is effective only for transparent fluids as reported in (Al Thobiani, 2011). In acoustic emission testing, another NDT method, high frequency AE waves are affected by transmission path and wave distortion which are technically considered as a major problem in AE condition monitoring of rotating machines (Towsyfyan *et al.*, 2018). Moreover, in most cases, distinguishing the AE signals from the background noise imposes several challenges. To overcome the deficiencies of aforementioned modalities, vibration analysis (Adams, 2019) has been proven to have promising potential for detecting cavitation in centrifugal pumps due to its nature using dynamic-response measurements. Centrifugal pumps, like other rotating machines (Shebin, 2016), produce a wide range of vibration frequencies that is minimum at the best efficiency point (BEP) of a pump. Any predominant fault occurring results in increased vibration level, and the magnitude of these vibration signatures go up as the fault develops. Additionally, vibration sensors are commercially viable with different technical specifications, e.g. different frequency ranges. Moreover, it is easier to position the accelerometers in many rotating machines, particularly in the different types of pumps .Therefore, vibration analysis has gained interest for reliable condition monitoring of centrifugal pumps and a considerable body of research has been concentrated to increase the probability of cavitation detection at earlier stage. This mainly includes analysis the vibration signatures using Wavelet transform and machine learning (Kamiel, 2015), neural networks (Nasiri *et al.*, 2011), decision tree (Sakthivel *et al.*, 2010), support vector machine (Xue *et al.*, 2014) and spectral and statistical methods (McKee *et al.*, 2015). Not limited to advanced signal processing techniques, research has also been reported on the application of time-domain vibration features such as root mean squared (RMS) (Al Thobiani, 2011 and Al-Hashmi *et al.*, 2007), peak value, kurtosis, crest factor (Al Thobiani, 2011), probability density function (Al Thobiani, 2011 and Al-Hashmi *et al.*, 2007) as well as spectral analysis (Al Thobiani, 2011; Al-Hashmi *et al.*, 2007 and Al-Hashmi *et al.*, 2017) for the purpose of monitoring the cavitation evolution in centrifugal pumps. In Ref (Tan *et al.*, 2008), envelope analysis has been successfully applied on vibration signatures to detect the development of cavitation in a wide range of operating conditions. Above understandings reveal vibration signatures are particularly useful to detect cavitation in centrifugal pumps. However, as a primary phase for accurate pump monitoring, few research works are available on the detection of incipient cavitation based on vibration measurements with positive outcomes. For instance, in Ref (Li *et al.*, 2018) an interesting vibration analysis algorithm has been introduced based on short time Fourier transform (STFT) and Wigner–Ville distribution (WVD) to detect the onset of cavitation. However, this approach relies on the relationship between vibration data and suction performance of pump. This paper attempts to fill this gap and presents an experimental study to demonstrate the competence of vibration analysis to detect the onset of cavitation in centrifugal pumps based on envelope spectrum analysis (as detailed in Section 4). This is of high importance in industrial applications to detect the incipient pump cavitation from the baseline (simply using of an accelerometer data), which is challenging for conventional signal processing methods (i.e. time domain and frequency domain features) as detailed in Sections 3.2-3.4.

2 EXPERIMENTS

2.1 Test Rig

Figure 1 shows the schematic illustration of the test rig designed and applied for condition monitoring of centrifugal pumps in this research. The rig consists of several sensors and components such as (1) water container (2) suction valve, (3) suction pressure transducer, (4) centrifugal pump, (5) accelerometer (6) discharge pressure transducer, (7) discharge valve (8) water flow meter, (9) hopper. The latter, hopper, has been added to the rig to calibrate the water flow meter. To simulate different levels of cavitation in the test system, throttling valves were installed at both sides, i.e. suction and discharge.

2.2. Measurement System

This study aims to detect the incipient cavitation in a Pedrollo type F32/200AH centrifugal pump. The pump has been designed to operate at rotational speed of 2755rpm with flow rates up to 300(l/min) that generates head of approximately 46m at designed flow rates. Figure 2 shows the schematic illustration of sensory and measurement system developed in this research for monitoring the incipient cavitation. The 300(l/min) is the design flow rate.

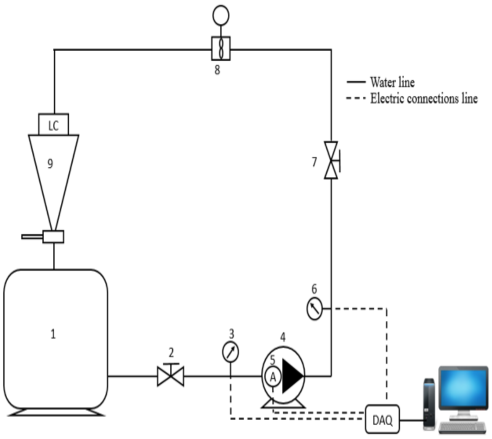
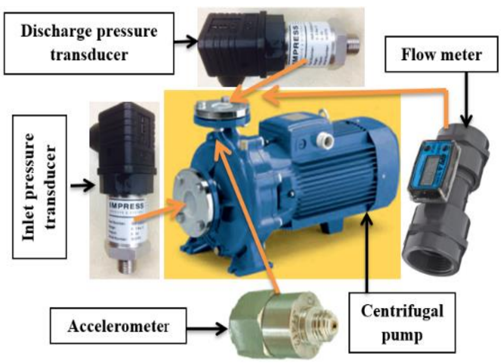
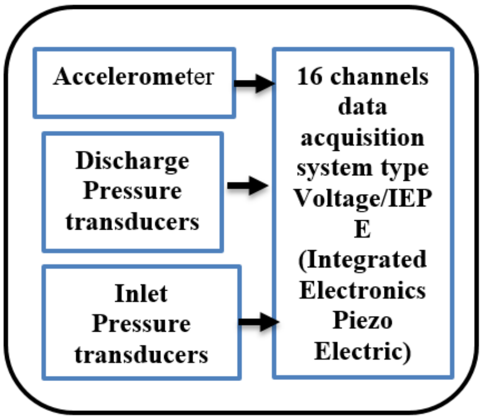


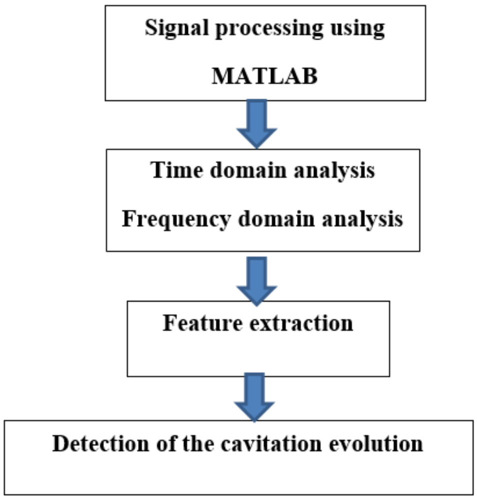
Fig. 1. Schematic illustration of the test rig (Al-Obaidi, 2018).



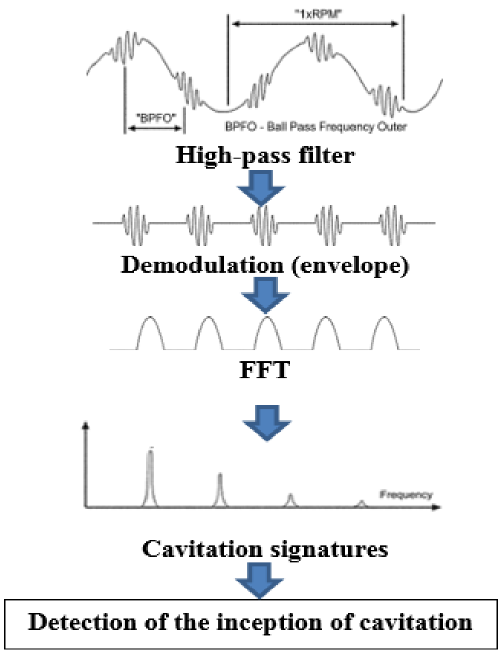
(1) Important experimental test rig parts



(2) Connections sensors and transducers with data acquisition system



(3) Signal processing using different features



(4) Envelope Analysis

Fig. 2. Schematic illustration of the different measurements system and experimental test procedure.

An IEPE type CA-YD-1182 accelerometer with an operating frequency range from 1 kHz to 15 kHz was employed to obtain the vibration signatures, allowing high frequency vibrations due to cavitation to be monitored. The accelerometer has been located closed to tongue volute region to gain optimal results. The exploratory experiments in present work have shown that this position of vibration sensor is less affected by the background noises.

Different Statistical features were used to analyse the vibration signal in time domain and these features can provide a good indicator of changes in the condition within the pump (Al-Obaidi, 2018) . An IMP type G5000-6A4-BCV-03-000 pressure transducer measured the high pressure at discharge pipe. To measure the low-pressure at suction pipe, an IMP type G1002-7A4-BCV-03-000 pressure transducer was used. The suction pressure transducer range between 0 and 5 bar and discharge pressure transducer was from 0 to 10 bar the accuracy for both transducer s about ±0.25%. The data recorded by pressure sensors are used to calculate the pump head across the pump as detailed in the next section. The signals from accelerometer and pressure sensors are amplified and acquired by 16-channel high speed data acquisition system at a sampling rate of 96 kHz. Details of the test rig, measurement method, data acquisition system have already been published in (Al-Obaidi, 2018). The flow of circulating fluid (water in this research) is controlled by a TM150 flow meter.

2.2 Test Procedure

Since centrifugal pumps are exposed to widely varying operating conditions during their service life, the experimental work in this research has been conducted at different flow rates in terms of percentage with respect to best efficiency point 0.4, 059,06, 076, 084, 0.92, 1.007,1.06, 1.1, 1.14, 1.17, 1.21%, 1.12, 1.23, 1.26 (l/min) to simulate different levels of cavitation in the test pump. The change in flow rate was achieved by throttling the discharge valves while the rotational speed of the pump was maintained at 2755 rpm. The recorded pressure data are then fed into a calculation algorithm to estimate the head of the pump. Using this test procedure, as it is evident in Fig. 3, the head of the pump decreases as the flow rate increases gradually. This demonstrates that the pressure at inlet eye of impeller geos down to the values lower than the water vapour pressure that technically implies the incipient pump cavitation. The idea is widely held that cavitation often begins at about a 3% drop in head from BEP, but this value will vary based on different parameters such as physical properties of the circulating fluid (Al Thobiani, 2011 and Alfayez *et al.*, 2005). For instance, in Ref (Gao *et al.*, 2017), the local maximum point of vibration RMS value with the corresponding 1% head drop, was defined as the vibration full cavitation point indicating that the onset of cavitation is much earlier than the conventional 3% head drop criterion. Therefore, approaches that are more reliable needed to identify the incipient cavitation.

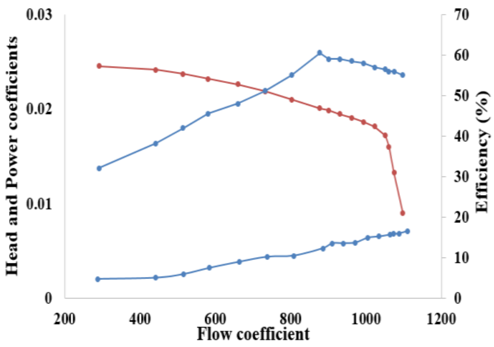


Fig. 3: Performance of the centrifugal pump (Head, power coefficients and efficiency) under different flow rates

(Zhu *et al.*, 2016) investigated the cavitation performance in a centrifugal pump in nuclear power system. The results have shown that when the inlet pressure decreases the cavitation occurrence increases and the inception of cavitation was happened at NPSH values lower than the 7.8 m. (Cucit *et al.*, 2018) tried to control occurrence of cavitation by controlling the rotational speed of a pump. They reported that the inception of cavitation occurs in the pump at NPSH of 3 m. In another work, (Li and Zhang, 2018) suggested a relationships between the NPSHA and performance variables of the pump. The results dimpled that the cavity shape, flow pattern and cavitation performance in the turbine model are distinguishably different as compared to the pump mode. (Lal and Deshmukh, 2018) analysed the centrifugal pump performance under various operating modes for the pump as a turbine. The result found that the maximum efficiency at design flow rate for the pump was around 2 % lower than pump mode. Also, the Net positive suction head was change by ± 3% for different loading from 60% to 120%. Moreover, the difference between NPSHR and NPSHA was minimum at 2.8 % for 100 % loading. (Wang *et al.*, 2018) studied the pressure fluctuation–vortex interaction with and without cavitation conditions in a low specific-speed centrifugal pump. The results revealed that the decrease in the pump head can lead to cavitation development.

(Al-Obaidi, 2019) monitored the centrifugal pump performance at different number of impeller blades under cavitation condition. The results shown that the velocity and pressure in the pump increased from inlet of the pump to outlet. Also, due to the high interactions between the rotor and stator at outlet the pressure at this region was bigger than at other pump sections. Moreover, the volume fraction distribution was firstly happened at suction impeller side especially at inlet eye zone. The result also found that as the flow rate and number of impeller blade increase the occurrence of cavitation increases.

To get insight into cavitation evolution in the test centrifugal pump, the related net positive section head (NPSH) curves in terms of flow rate values, according to ISO 3555, are presented in Fig. 4. To

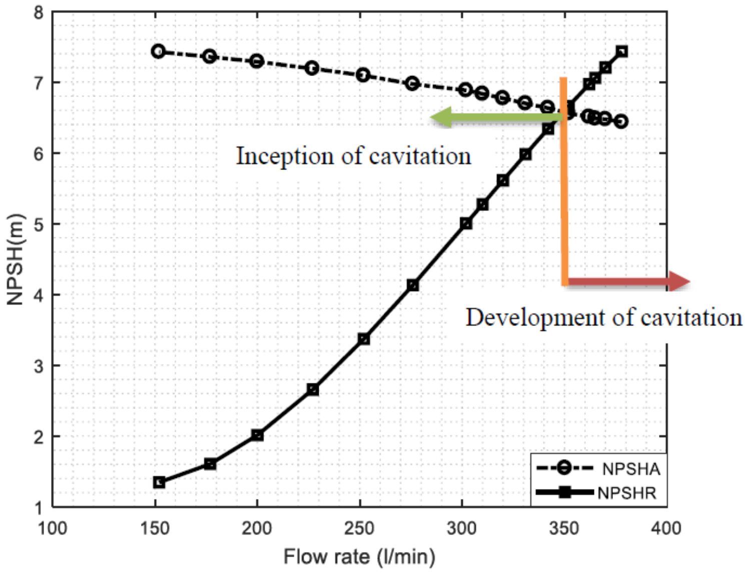


Fig. 4. Relationship between NPSHR and NPSHA of the test centrifugal pump at different flow rates.

calculate NPSHA (NPSH available), the rotational speed of shaft is kept constant at 2755rpm and the speed can be controlled during the test using control speed regulator. The flow rate is increased gradually through progressively throttling the discharge valve whilst the suction valve was fully open. The NPSHR (NPSH required) curve for the centrifugal pump was provided by the maker data. As it is evident in Fig. 4, at flow rates lower than 300(l/min) the NPSHA curve is well higher than the NPSHR curve and cavitation does not occur. By further increasing the flow rate, the curves become closer until crossing each other at the flow rate of 350 (l/min). Technically the onset of cavitation, where cavitation becomes detectable, is located between these two limits, i.e. 300 to 350 (l/min). The computational fluid dynamic analysis
(CFD) presented in Ref (Al-Obaidi, 2018) proves that the inception of cavitation occurs at the flow rate of 331 (l/min) for the experimental set up presented in this section. It has also been reported that at the flow rates lower than 331(l/min) small inception of cavitation occurs on the impeller blades (Al-Obaidi, 2018). By increasing the flow rate higher than 350(l/min), cavitation develops in the pump and it becomes more severe by the flow rate increase. By furthered increasing the fluid flow more than 360(l/min), the pressure decreases at the eye of the impeller, and hence, the NPSHA becomes smaller than the NPSHR and fully developed cavitation occurs. Based on these characteristics, therefore, different levels of cavitation i.e. no cavitation or baseline, inception of cavitation, developed cavitation and fully developed cavitation will be experimentally generated in the test pump. Therefore, this set up allows to examine the competence of vibration signals to detect the onset of cavitation as well as to characterise the cavitation evolution in the test pump.

3. RESULTS AND DISCUSSION

3.1. Identification of the Cavitation Induced Vibrations

This section aims to identify a vibration frequency range that can present the cavitation-induced vibrations in the test centrifugal pump. It is immediately noted that when cavitation occurs, the flow conditions such as density and viscosity changes locally. The effect of viscosity change is beyond the scope of present work and is of high interest for future activities.

To get insight into the identification of these signatures from the background noises, a waterfall plot is used. This allows comparison of the spectrums at different flow rates and hence to extract the correct signature from wide range of frequency components.

As it is evident in Fig. 5 the amplitude of the low and mid frequencies, i.e. 0-8 kHz, do not change significantly with the flow rate increase, except for the frequency range of 5-8 kHz at very high flow rates. It is generally accepted that the influence from other vibration sources such as hydraulic forces and recirculation is usually large for mid frequencies, e.g. 5-8 kHz (Al-Obaidi, 2018). This gives a solid conclusion that the low and mid frequencies are related to background noises (e.g. hydraulic forces, rotational frequency of shaft, first blades passing frequency and their harmonics) and hence cannot represent cavitation induced vibration. However, as it is evident in Fig. 5 the vibration energy concentrated mainly in the frequency range between 8-15 kHz. At the flow rate, less than 300(l/min), i.e. in design flow rate range, the vibration amplitudes remain constant and does not show a notable change by the flow rate increase. However, a notable increase in the vibration level is evident when the flow rate exceeds 300 (l/min). That is in a good agreement with the cavitation evolution of the tested pump discussed in the Section 2.3.

This gives good evidence that the mentioned frequency range can correctly present the cavitation induced vibrations of the tested system and therefore can be used for accurate pump monitoring. Thus, for the remainder of the paper, a high pass filter was designed using MATLAB codes and applied to vibration raw data. Therefore, research will be developed based on three flow rates i.e. 302 (l/min), 331 (l/min) and 352 (l/min)

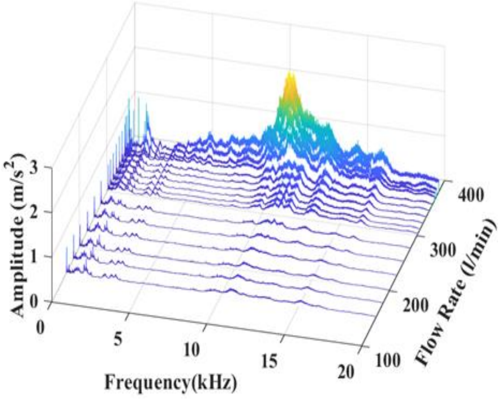


Fig. 5. Waterfall of the vibration spectra at different flow rates.

that represent baseline (no cavitation), inception of cavitation (based on CFD analysis in (Al-Obaidi, 2018) and developed cavitation respectively.

3.2. Vibration Raw Data

Figure 6 presents typical vibration signatures at different flow rate settings. As it is evident, by increasing the flow rate gradually the vibration amplitudes go up. Moreover, the number of transient (or burst) type vibration responses increases significantly. These impulsive events are high-energy, high-frequency events of very short duration. Since more bubbles nucleate, grow and then collapse, a higher vibration energy is released in a short period of time that generates transient responses. The higher the flow rate, the more transient type vibration is generated. Therefore, this speed dependency of vibration signatures to the cavitation evolution allows development of cavitation to be monitored accurately. However, it is challenging to distinct the inception of cavitation from the baseline as shown in Fig. 7.

3.3. Time Domain Features

Time domain features extracted from vibration signals, as indicators sensitive to impulsive vibrations, are widely used for the purpose of early fault detection in rotating machines. Several methods used either the peak or the RMS value; others used their ratio, the crest factor (Shebin, 2016). These features have been extracted from the filtered vibration data as presented in Figs. 8-10. The vertical line indicates the onset of cavitation based on CFD analysis presented in (Al-Obaidi, 2018). As it is evident in Figs. 8,9, peak value along with RMS is able to characterise the cavitation development specifically for the flow rates higher than 350 (l/min), however, they are insensitive to the onset of cavitation, i.e. the flow rate of 331 (l/min) as indicated in figures. At the onset of cavitation, both features see the values similar to the baseline i.e. flow rate of 302 (l/min). It is immediately noted that RMS value does not see a notable change for the design flow rate range of the pump, i.e. flow rates less than 302 (l/min), indicating that RMS (as a measure of vibration responses of the structure) is a reliable indicator for normal operating set ups.pump, i.e. flow rates less than 302 (l/min), indicating that RMS (as a measure of vibration responses of the structure) is a reliable indicator for normal operating set ups. Crest factor, in theory (Shebin, 2016), is more sensitive to the inception of cavitation when the peak value is high, and the RMS is low. After the development of cavitation, the RMS value increases significantly, and the crest factor should go down. The latter achieved experimentally whilst the former, i.e. the sensitivity of crest factor to incipient cavitation, is not evident in Fig. 10. Therefore, these indicators are not sensitive enough to the inception of cavitation and do not make a clear distinct with the baseline whilst they can reasonably manifest the cavitation evolution according to NPSH curves of the pump.

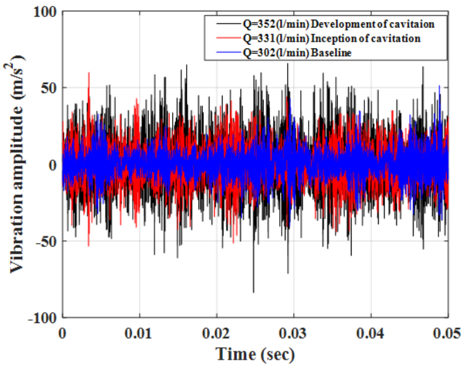


Fig. 6. Vibration raw signal for baseline, inception and development of cavitation.

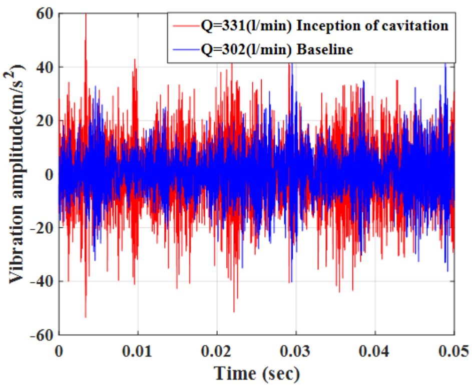


Fig. 7. Comparison of vibration signals: baseline against inception of cavitation.

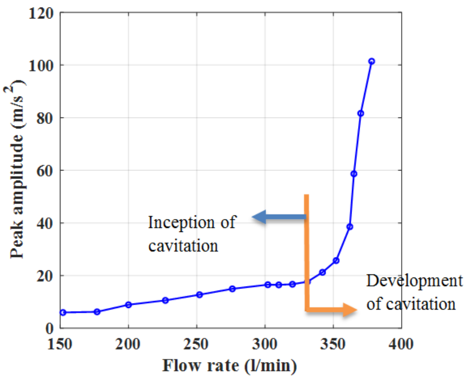


Fig. 8. Peak value of vibration signals at different flow rates.

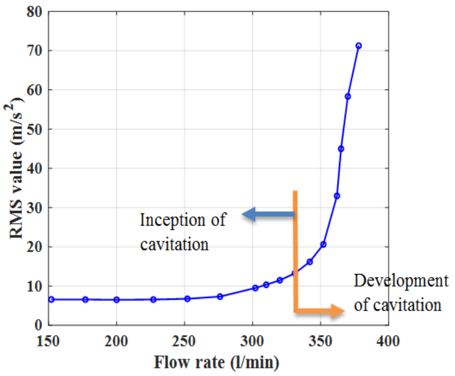


Fig. 9. RMS value of vibration signals at different flow rates.

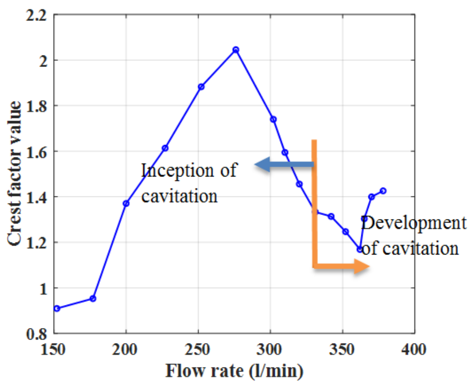


Fig. 10. Crest factor value of vibration signals at different flow rates.

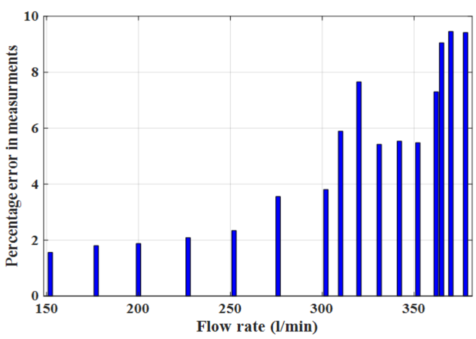


Fig. 11. Percent error in peak amplitudes.

To ensure the repeatability of vibration measurements, the error analysis has been carried out on two different tests for the peak values, Fig. 11. As it is evident, the percentage error is in an acceptable range (less than 10%).

3.4. Frequency Domain Analysis

In spectral analysis, particular frequency component corresponds to cavitation induced vibrations are investigated. Useful information provided by the frequency spectra is often the change of the frequency components and their amplitudes for different flow rate settings. Based on Fig. 12 the difference between the healthy baseline and the onset of cavitation becomes more evident in the spectral analysis compared with vibration data. As it is observed, the amplitude of vibration spectra is higher for the higher flow rates. However, the vibration spectrums are dangerously similar, and a clear distinct is not evident in frequency components during the cavitation evolution. Therefore, more robust signal processing techniques needed to ensure the inception of cavitation is separated reliably from the baseline.

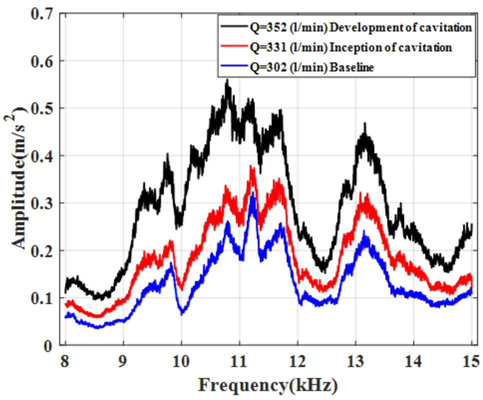


Fig. 12. Spectral analysis of vibration signals at different level of cavitation.

4. Envelope Spectrum Analysis

Envelope analysis is a signal processing technique, also known as amplitude demodulation, uses the high frequency components of the defect modulated vibration signal and demodulate it to obtain the vibration signature. The technique is particularly useful to reveals signals associated with impulse or impact events (Geropp, 1997) (e.g. cavitation bubble collapse). As has already been discussed, these signatures may remain dangerously hidden in time domain features as well as in vibration spectrum. In envelope analysis, the vibration signals are first filtered within a high pass filter that eliminates low frequency components e.g. blade passing frequency. After the vibration signals being filtered, the resulting signals consist of a series of exponentially decaying impulse responses acting as carrier modulated with a series of impulses produced by the defect, e.g. cavitation. This implies that information on the inception, evolution and periodicity of cavitation is available in the modulated signal (Shebin, 2016 and Miljković, 2015). The cavitation signatures can be obtained by extracting the envelope, or in other words by removing the carrier wave. Hilbert transform specifically facilitates the implementation of envelope analysis, by converting signal to an analytical form, whose magnitude is original signal's envelope (Laila *et al.,* 2009). Conventionally the Hilbert transform, as a specific linear operator, of a continuous signal $X(t)$ is computed as (Laila *et al.,* 2009):

$$\hat{X}(t) = \frac{1}{\pi} PV \int_{-\infty}^{+\infty} \frac{X(t)}{t-\tau} d\tau \tag{1}$$

Where $\bar{X}(t)$ is the Hilbert transform of signal $X(t)$ and the Cauchy principle value, PV, is taken from the improper integral. The Hilbert transform has a particularly simple representation in the frequency domain and imparts a $\frac{\pi}{2}$ radian phase shift to every Fourier component of a function (Immovilli *et al.,* 2010). The Fourier transform of the Hilbert transform can be expressed as:

$$\hat{X}(\omega) = -i \, sgn(\omega) X(\omega) \tag{2}$$

Where $X(\omega)$ is the Fourier transform of signal $X(t)$ and sgn is the well-known Signum function. The discrete Hilbert transform can be understood to be the convolution of discrete domain sequences, $X(n)$ and the impulse response of the discrete Hilbert transform, $h(n)$, as following (Padala *et al.,* 1997):

$$\hat{X}(n) = X(n) * h(n) \tag{3}$$

Where $h(n)$ is given by

$$h(n) = \begin{cases} \dfrac{2\sin^2\left(\pi n/2\right)}{\pi n} & n \neq 0 \\ 0 & n = 0 \end{cases} \tag{4}$$

The transfer function of the discrete Hilbert transform is defined as (Pei *et al.,* 2000):

$$H(\omega) = \begin{cases} i & 0 < \omega < \pi \\ 0 & \omega = 0, \pi \\ -i & -\pi < \omega < 0 \end{cases} \tag{5}$$

Several studies demonstrate that attempts have been made for vibration based fault detection of rotating machines using of envelope analysis including gearboxes (Zhou *et al.,* 2018 and Wang *et al.,* 2017) and bearings (Patel *et al.,* 2012 and Randall *et al.,* 2001). A very good review on the state of the art in the field with focus on organising dispread research papers into a structured comprehensive framework is found in (Abboud *et al.,* 2017). In Fig. 12 the envelope of vibration signals recorded at the inception of cavitation is compared with the baseline. As it is observed, the difference between the baseline and the inception of cavitation is not yet evident in the demodulated signal.

Therefore, the envelope spectrum, i.e. the Fast Fourier Transform (FFT) of demodulated signal obtained through Hilbert transform, will be implemented in Fig. 13 to reveal the dominant peaks which are not shown in vibration spectrum i.e. Fig. 13. As it is evident, an envelope spectra is the same as conventional spectra in appearance, however, it is more sensitive to cavitation induced vibrations and hence has a promising potential to develop more advanced diagnostic technologies to detect the incipit cavitation at earlier stage.

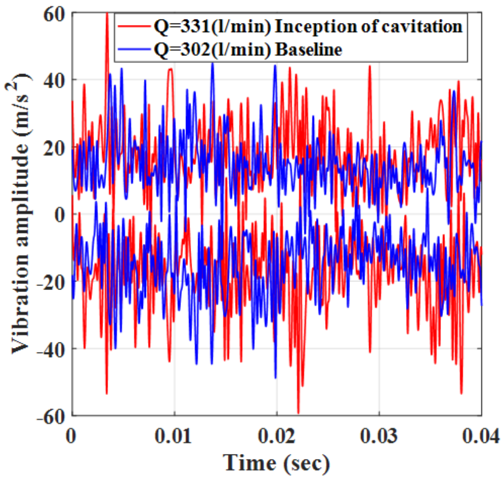


Fig. 13. Envelope of vibration signal at baseline and inception of cavitation.

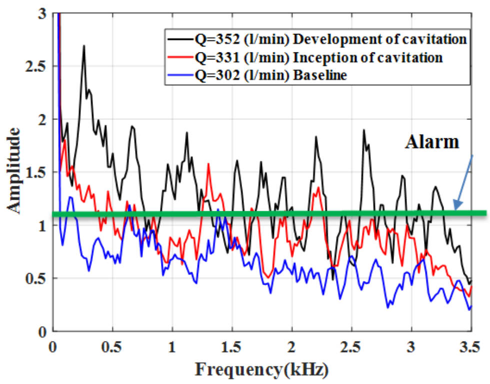


Fig. 14. Envelope spectrum at baseline and different level of cavitation.

As it is evident in Fig. 14, envelope spectrum allows a clear separation of the inception of cavitation from the healthy baseline as the high amplitude components is not observed in the baseline. It is immediately noted that the low energy peaks in the envelope spectrum of the baseline can be understood to be the effect of small inception of cavitation that may partially occur on the impeller blades at the flow rates higher than 300 (l/min). Moreover, the amplitude along with periodicity of the peaks in the envelope spectrum increases with the flow rate increase indicating the cavitation evolution in the test system. This gives a strong potential in order to develop more advanced vibration based diagnostic technologies to improve the reliability of cavitation detection in centrifugal pumps at earlier stages and prevent further cavitation by initiating an alarm on envelope spectra.

5. CONCLUSION

This paper demonstrates the competence of vibration signatures to detect the inception of cavitation in centrifugal pumps. To investigate the changes in vibration signal parameters under different flow rates and feasibility of predicting the onset of cavitation, an experimental study was carried out to simulate different levels of cavitation on a purpose built test rig. The analysis of results produces the following key points:

1. The amplitude of the low frequency vibrations, i.e. 0-8 kHz, does not change significantly with the flow rate increase, indicating that the low and mid frequencies are related to background noises.
2. The vibration energy concentrated mainly in the frequency range between 8-15 kHz. At the flow rate less than 300(l/min), i.e. in design flow rate range, the vibration amplitudes remain constant and does not show a notable change by the flow rate increase. However, a notable increase in the vibration level for the frequency range between 8-15 kHz is evident when the flow rate exceeds 300 (l/min). This gives a solid conclusion that this high frequency range properly represents the cavitation induced vibrations. Therefore, a high pass filter was designed using MATLAB codes and applied to vibration raw data.
3. The analysis of vibration raw data shows that as the flow rate is gradually increased in the test system, the vibration amplitudes go up. The higher the flow rate, the more transient type vibration signals are generated as well. These impulsive events are high-energy, high-frequency events due cavitation bubble collapse. However, it is challenging to distinct the inception of cavitation from the baseline based on the vibration raw data.
4. The analysis of time domain features has shown that the peak value along with RMS is able to characterise the cavitation development specifically for the flow rates higher than 350 (l/min). However, these indicators are not sensitive enough to the inception of cavitation and do not make a clear distinct from the baseline.
5. The difference between the healthy baseline and the onset of cavitation becomes more evident in spectral analysis compared with vibration raw data. However, a clear distinct is not evident in spectra during the cavitation evolution.
6. The envelope spectrum allows a clear separation of the inception of cavitation from the healthy baseline as the high amplitude components is not observed at the flow rates in design flow rate range of the pump, i.e. baseline.

Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

Funding: The Ministry of Higher Education and Scientific Research (Iraq).

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

ACKNOWLEDGMENT

The authors would like to thank Mustansiriyah University (www.uomustansiriyah.edu.iq) Baghdad – Iraq for its support in the present work. The first author also would like to gratefully acknowledge the University of Huddersfield (UK) due to providing laboratory facilities and data collection that has been carried out during his PhD studies at the university of Huddersfield (UK).

REFERENCES

Abboud, D., J. Antoni, S. Sieg-Zieba and M. Eltabach (2017). Envelope analysis of rotating machine vibrations in variable speed conditions: *A comprehensive treatment.. Mechanical Systems and Signal Processing* 84, 200-226.

Adams, M. L. (2009). *Rotating machinery vibration: from analysis to troubleshooting*. CRC Press. Taylor & Francis Group.

Al Thobiani, F. (2011). *The non-intrusive detection of incipient cavitation in centrifugal pumps*. Huddersfield, UK, (Doctoral dissertation, University of Huddersfield.

Al-Arabi, A. A. B., S. M. A. Selim, R. Saidur, S. N. Kazi and G. G. Duffy (2011). Detection of Cavitation in Centrifugal Pumps. *Australian Journal of Basic and Applied Sciences* 5(10), 1260-1267.

Alfayez, L., D. Mba and G. Dyson (2005). The application of acoustic emission for detecting incipient cavitation and the best efficiency point of a 60 kW centrifugal pump: case study. *Ndt & E International* 38(5), 354-358.

Al-Hashmi, S. A., A. B. Mohammed, I. Nasir and M. Elhaj (2017). Spectrum Analysis of Vibration Signals for Cavitation Monitoring.

Journal of Pure & Applied Sciences 16(1).

Al-Hashmi, S. A., R. Mohamed and A. Ball (2007). Processing Vibration Signals For Cavitation Detection. *Journal of Sebha Univ.(Pure and Applied Sc.)*6(2), 50.

Al-Obaidi, A. (2018). *Experimental and Numerical Investigations on the Cavitation Phenomenon in a Centrifugal Pump*. Huddersfield, UK. (Doctoral dissertation, University of Huddersfield.

Al-Obaidi, A. (2019). Monitoring the Performance of Centrifugal Pump under Single-Phase and Cavitation Condition: A CFD Analysis of the Number of Impeller Blades. *Journal of Applied Fluid Mechanics* 12(2), 445-459.

Binama, M., A. Muhirwa and E. Bisengimana (2016). Cavitation effects in centrifugal pumps-A review. Binama Maxime. *International Journal of Engineering Research and Applications* 6(5), 52-63.

Čdina, M. (2003). Detection of cavitation phenomenon in a centrifugal pump using audible sound. *Mechanical systems and signal processing* 17(6), 1335-1347.

Chudina, M. (2003). Noise as an Indicator of Cavitation in a Centrifugal Pump. *Acoustical Physics* 49(4), p. 463-474.

Cucit, V., F. Burlon, G. Fenu, R. Furlanetto, F. A. Pellegrino and M. Simonato (2018). A control system for preventing cavitation of centrifugal pumps. *Energy Procedia* 148, 242-249.

Gao, B., P. Guo, N. Zhang, Z. Li and M. Yang (2017). Experimental Investigation on Cavitating Flow Induced Vibration Characteristics of a Low Specific Speed Centrifugal Pump. *Shock and Vibration* 2017,12.

Geropp, B. (1997). Envelope Analysis-A Signal Analysis Technique for Early Detection and Isolation of Machine Faults. *IFAC Proceedings* 30(18), 977-981.

Immovilli, F., A. Bellini, R. Rubini and C. Tassoni (2010). Diagnosis of bearing faults in induction machines by vibration or current signals: A critical comparison. *IEEE*.

Kamiel, B. P. (2015). *Vibration-based multi-fault diagnosis for centrifugal pumps*. Perth, Western Australia. (Doctoral dissertation, Curtin University).

Karassik,I. and J. F. Gülich (2008). *Centrifugal pumps* (Vol. 2). Berlin: Springer.

Laila, D. S., M. Larsson, B. C. Pal and P. Korba (2009). Nonlinear damping computation and envelope detection using Hilbert transform and its application to power systems wide area monitoring. In *Power & Energy Society General Meeting*, PES'09. IEEE (pp. 1-7). IEEE.

Lal, B. and T. S. Deshmukh (2018). Performance Analysis of Centrifugal Pump at Different Operating Mode. *International Journal Online Of Science* 4(11), 8-8.

Li, W. and Y. Zhang (2018). Numerical simulation of cavitating flow in a centrifugal pump as turbine. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* 232(2), 135-154.

Li, Y., G. Feng, X. Li, Q. Si and Z. Zhu (2018). An experimental study on the cavitation vibration characteristics of a centrifugal pump at normal flow rate. *Journal of Mechanical Science and Technology* 32(10), 4711-4720.

McKee, K. K., G. L. Forbes, I. Mazhar, R. Entwistle, M. Hodkiewicz and I. Howard (2015). A vibration cavitation sensitivity parameter based on spectral and statistical methods.

McKee, K., G. Forbes, M. I. Mazhar, R. Entwistle and I. Howard (2011). A review of major centrifugal pump failure modes with application to the water supply and sewerage industries. In *ICOMS Asset Management Conference*.

Miljković, D. (2015). Brief Review of Vibration Based Machine Condition Monitoring. HDKBR INFO Magazin, 5(2), 14-23. *Transactions on Industry Applications* 46(4), 1350-1359.

Nasiri, M. R., M. J. Mahjoob and H. Vahid-Alizadeh (2011, April). Vibration signature analysis for detecting cavitation in centrifugal pumps using neural networks. In Mechatronics (ICM), 2011 *IEEE International Conference* on (632-635). IEEE.

Padala, S. K. and K. M. M. Prabhu (1997). Systolic arrays for the discrete Hilbert transform. *IEE Proceedings-Circuits, Devices and Systems* 144(5), 259-264.

Patel, V. N., N. Tandon and R. K. Pandey (2012). Defect detection in deep groove ball bearing in presence of external vibration using envelope analysis and Duffing oscillator. *Measurement* 45(5), 960-970.

Pei, S. C. and M. H. Yeh (2000). Discrete fractional Hilbert transform. IEEE Transactions on Circuits and Systems II: *Analog and Digital Signal Processing* 47(11), 1307-1311.

Randall, R. B., J. Antoni and S. Chobsaard (2001). The relationship between spectral correlation and envelope analysis in the diagnostics of bearing faults and other cyclostationary machine signals. *Mechanical systems and signal processing* 15(5), 945-962.

Sakthivel, N. R., V. Sugumaran and S. Babudevasenapati (2010).Vibration based fault diagnosis of monoblock centrifugal pump using decision tree. *Expert Systems with Applications* 37(6), 4040-4049.

Samanipour, P., J. Poshtan and H. Sadeghi (2017). Cavitation detection in centrifugal pumps using pressure time-domain features. *Turkish Journal of Electrical Engineering & Computer Sciences* 25(5), 4287-4298.

Sánchez, W., C. Carvajal, J. Poalacin and E. Salazar (2018, April). Detection of cavitation in centrifugal pump for vibration analysis. In 2018 4th *International Conference on Control, Automation and Robotics (ICCAR)* (pp. 460-464). IEEE.

Shebin, E. L (2016). Fault Diagnosis of Rotating Machinery based on vibration analysis. *International Journal of Advanced Engineering and Global Technology I* 4(1).

Soni, S. (2018). Increase productivity of centrifugal pump by detection of cavitation phenomena. *Indian Journal of Applied Research* 7(7).

Stan, M., I. Pana, M. Minescu, A. Ichim and C. Teodoriu (2018). Centrifugal Pump Monitoring and Determination of Pump Characteristic Curves Using Experimental and Analytical Solutions. *Processes* 6(2), 18.

Stopa, M. M., B. J. Cardoso Filho and C. B. Martinez (2014). Incipient detection of cavitation phenomenon in centrifugal pumps. *IEEE Transactions on industry applications* 50(1), 120-126.

Tan, C. Z. and M. S. Leong (2008). An experimental study of cavitation detection in a centrifugal pump using envelope analysis. *Journal of System Design and Dynamics* 2(1), 274-285.

Towsyfyan, H., F. Gu, A. D. Ball and B. Liang (2018). Modelling acoustic emissions generated by tribological behaviour of mechanical seals for condition monitoring and fault detection.*Tribology International* 125, 46-58.

Wang, C., Y. Zhang, Z. Li, A. Xu, C. Xu and Z. Shi (2018). Pressure fluctuation–vortex interaction in an ultra-low specific-speed centrifugal pump. *Journal of Low Frequency Noise, Vibration and Active Control*.

Wang, L., Y. Shao, P. Sun, F. Guo, J. Liu, S. Street and B. District (2017). Local fault diagnosis of non-stationary gearbox based on order envelope analysis. *International Journal of COMADEM* 20(4).

Xue, H., Z. Li, H. Wang and P. Chen (2014). Intelligent diagnosis method for centrifugal pump system using vibration signal and support vector machine. Shock and Vibration. *Expert systems with applications* 42(1), 67-78.

Yan, Z., J. Liu, B. Chen, X. Cheng and J. Yang (2015). Fluid cavitation detection method with phase demodulation of ultrasonic signal. *Applied Acoustics* 87, 198-204.

Zhou, L., F. Duan, D. Mba, W. Wang and S. Ojolo (2018). Using frequency domain analysis techniques for diagnosis of planetary bearing defect in a CH-46E helicopter aft gearbox. *Engineering Failure Analysis* 92, 71-83.

Zhu, R., Q. Fu, Y. Liu, B. He and X. Wang (2016). The research and test of the cavitation performance of first stage impeller of centrifugal charging pump in nuclear power stations. *Nuclear Engineering and Design* 300, 74-84.