An Experimental Study of Cavitation Detection in a Centrifugal Pump Using Envelope Analysis*

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Abstract

Cavitation represents one of the most common faults in pumps and could potentially lead to a series of failure in mechanical seal, impeller, bearing, shaft, motor, etc. In this work, an experimental rig was setup to investigate cavitation detection using vibration envelope analysis method, and measured parameters included sound, pressure and flow rate for feasibility of cavitation detection. The experiment testing included 3 operating points of the centrifugal pump (B.E.P, 90% of B.E.P and 80% of B.E.P). Suction pressure of the centrifugal pump was decreased gradually until the inception point of cavitation. Vibration measurements were undertaken at various locations including casing, bearing, suction and discharge flange of the centrifugal pump. Comparisons of envelope spectrums under cavitating and non-cavitating conditions were presented. Envelope analysis was proven useful in detecting cavitation over the 3 testing conditions. During the normal operating condition, vibration peak synchronous to rotational speed was more pronounced. It was however during cavitation condition, the half order sub-harmonic vibration component was clearly evident in the envelope spectrums undertaken at all measurement locations except at the pump bearing. The possible explanation of the strong sub-harmonic (½ of BPF) during cavitation existence in the centrifugal pump was due to insufficient time for the bubbles to collapse completely before the end of the single cycle.

Key words: Cavitation, Envelope Analysis, Centrifugal Pump

1. Introduction

Pumps are commonly used in all industries. These industries include water, oil and gas, petrochemical, power generation, etc. Various faults can occur in the centrifugal pump that results in low efficiency operation of centrifugal pump. The survey carried out on behalf of the German Engineering Federation (VDMA) showed that 80% of the pump failures in the chemical and process industries were from cavitation, dry run, gas containing liquids, externally excited vibrations, imbalance, wear of bearing and blockage (pressure side and/or suction side gate valve closed). It was found that cavitation is however the most common faults.

Cavitations in the industry are often with serious consequence. On 15 November 1999, H-II Flight #8 was officially launched from Tanegashima Space Center, Japan. The first stage engine suddenly failed after 4 minutes upon launching. Investigation showed that rotating cavitation in the fuel turbo pump was one of the causes (1). The estimated causes of failure include vibration forced by rotating cavitation, and resonance generated by the pressure oscillation around the natural frequency of 3.2 kHz of the inducer blade.
Farhat et al. (1996) had reported that cavitation was more readily detected by vibration envelope (2). Kaye (1999) reported on cavitation monitoring of hydraulic machines by vibration envelope analysis, where the viability using envelope analysis was demonstrated. A number of analysis method were developed and used together to investigate cavitation behaviour in model and prototype Francis turbines (3). Work on cavitation classification of hydraulic turbine done by Kaye and Farhat (2002) showed that envelope analysis is the most suitable way to detect and quantify the cavitation in the turbines (4). Vibration data of cavitation on a Francis turbine was analyzed by Escaler et al. (5). There were limited works on the study of cavitation on hydraulic machines using Envelope analysis. It was the intention of this work to investigate the feasibility of envelope analysis on cavitation detection for a centrifugal pump.

2. Overview of Envelope Analysis Theories

Envelope analysis is a signal processing technique, also known as amplitude demodulation. The sequence of data processing involved in this technique is shown in Figure 2.1. The vibration signal in time domain is first filtered within a band pass. The filter band is chosen to include the frequency range of cavitation. This also eliminates low frequency components that are common in rotating machinery including misalignment, unbalance. While all these sources of vibration are potentially present in rotating machinery they are however of limited interest in cavitation detection.

After the vibration time signal being filtered, the resulting signals would be rectified. Part of the enveloping process is to take the time wave form and fold the bottom half up onto the top half of the signal. It is why the time signal after filtered is seen above the zero reference line. To rectify the signal, a Hilbert Transform is done. The envelope circuit (detector) would square the filtered time domain signal. When a harmonic series is multiplied by itself, the resultant series is a summation of all the sums and difference components. After the signal is being band-pass filtering, all the remaining defect components would be processed normally by the FFT conversion.

This whole process is also known as amplitude demodulation, i.e an AM radio strips away the carrier frequency and plays the music. In this case, the machine rotational components (unbalance, misalignment, etc.,) are eliminated and are left with the impact-related signals such as bearing defects, gear etc. Finally, the signals being demodulated are shown as “envelope spectrum”. The envelope spectrum would reveal the dominant peaks which are not shown in FFT.

![Figure 2.1 Summary of Envelope Analysis Technique](image)
In most modern vibration analyzers, envelope analysis is one of the built-in functions. The selection of band-pass filter normally is based on the running speed of the machine. The selection of envelope band-pass filter range is important as it affects the results of envelope spectrum. Each filter range will produce different results on the envelope spectrum. These filters embedded in SKF Microlog Analyzer are Butterworth type, with 3-pole skirts. It is able to simulate these filters in MATLAB program to be equivalent to enveloping band-pass filters. The recommended accelerometer sensor sensitivity to optimize the signal-to-noise ratio lies in the range from 10 to 500 mV/G. The accelerometer sensor sensitivity that is being used in our case is reported as 100 mV/G, which is suitable.

3. Experimental Setup

An experimental test rig was setup in the laboratory for vibration studies of cavitation in a centrifugal pump. The test rig consisted of a single stage end-suction centrifugal pump, tank, and a vacuum pump. The test facility is as shown in Figure 3.1. The pump had 6 vanes made of cast iron, and was directly coupled to a 3 phase motor with a rotational speed of 2500 rpm. The centrifugal pump was connected to the suction side of a vacuum tank, and the discharge side routed back to the vacuum tank for a closed loop flow. A vacuum pump was used to induce a negative pressure at the top of the suction tank. The water level in the tank was always maintained higher than the water inlet of the tank.

After setting up the entire experimental rig (see Figure 3.2), testing commenced by first measuring the vibration signals of the normal operating condition. Having measured the baseline condition, vacuum pump was then switched on to reduce the pressure at the suction pump until the cavitation was induced. For example, pressure of suction pump was initially 0.9 bar under normal operating condition. It was gradually reduced by the vacuum pump until 0.2 bar. Vibration measurement, sound pressure level, pressure and flow rate value were recorded during the gradual decrease process until the cavitation point.

Three normal operating conditions (which are B.E.P, 80% of B.E.P and 90% of B.E.P) were tested to verify the consistency of the findings. It is to confirm the findings are not only limited to certain condition. The condition was designed to examine whether if the cavitation could be differentiated on the vibration spectrum specifically and other parameters on the experimental rig. Vibration measurements were undertaken at various location of the centrifugal pump such as the casing (measured in axial – front, axial – rear, radial), bearing (measured in horizontal and vertical direction), suction flange and discharge
flange as well. The test variables of this experimental rig include suction pressure of the centrifugal pump, the pressure at the top of the vacuum tank, and operating point of the centrifugal pump.

4. Experimental Results

Figure 4.1 Head vs Flow of the Centrifugal Pump

The initial testing condition 1 for normal running condition was approximately at 80% of B.E.P (i.e. 0.8 B.E.P). Suction pressure was gradually decreased from this point until cavitation was being induced (as shown in Figure 4.1). The running speed of the centrifugal pump was about 2400 rpm (40Hz). For testing condition 2, the normal running condition was approximately at 90% of the B.E.P (i.e. 0.9 B.E.P). Furthermore, initial testing condition 3 for normal running condition was at the best efficient point (B.E.P). The running speed for both testing condition 2 and 3 was reported about 2500 rpm (equivalent of 42 Hz).

Table 4.1 tabulates the locations of vibration measurements undertaken and repeated for all three test conditions. The photograph of one of the measurement locations is shown in Figure 3.2. Vibration data are presented in envelope spectrums.

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pump Casing (Rear)</td>
<td>Axial</td>
</tr>
<tr>
<td>2</td>
<td>Pump Casing (Front)</td>
<td>Axial</td>
</tr>
<tr>
<td>3</td>
<td>Pump Casing</td>
<td>Radial</td>
</tr>
<tr>
<td>4</td>
<td>Suction Flange</td>
<td>Axial</td>
</tr>
<tr>
<td>5</td>
<td>Discharge Flange</td>
<td>Vertical</td>
</tr>
<tr>
<td>6</td>
<td>Bearing</td>
<td>Horizontal</td>
</tr>
<tr>
<td>7</td>
<td>Bearing</td>
<td>Vertical</td>
</tr>
</tbody>
</table>

Measurements at the pump casing (rear) under testing condition 1 in term of axial direction showed vibration response increase at 120 Hz (half of the BPF), 240 Hz (BPF), 279 Hz (7x rpm), 358 Hz (9x rpm) and 478 Hz (12x rpm) in particular; see Figure 4.2(a). Multiples of harmonics and raise floor noise in the envelope spectrums of cavitation condition was therefore clearly evident. At normal operating condition, the peak of envelope spectrums was observed at the 1x rpm, which was governed by the rotational
speed. The envelope spectrum of normal operating condition did not demonstrate high vibration response peaks, nor was the harmonics multiplies so clearly evident. Rolling element defect frequency at 141 Hz was also noted during normal operating condition but its vibration amplitude was significantly lower than the peak at $\frac{1}{2}$ of the BPF. For testing condition 2, prominent vibration peak at 125 Hz ($\frac{1}{2}$ of BPF) was observed during the cavitation condition; see Figure 4.2(b). Prior to cavitation, there was vibration response peak observed at 42 Hz (1x rpm) for both testing condition 2 and testing condition 3; see Figure 4.2(c). The vibration response of cavitation condition up to 1000 Hz was generally higher than normal condition under all three testing condition.

Figure 4.2: Envelope Spectrum of Cavitation and Normal Operating Condition at Pump Casing (Rear) in Axial Direction
The most dominant peak during cavitation condition was observed at 120 Hz (½ of the BPF) which measured at the pump casing (front) in axial direction under testing condition 1; Figure 4.3(a). Pertinent peaks include 40 Hz (1x rpm), 81 Hz (~2x rpm), 160 Hz (4x rpm), 240 Hz (BPF), etc. Multiples of harmonics and vibration increase up to 1000 Hz was clearly evident. Vibration spectra of normal operating condition was obviously governed by the rotational speed, as the peak at 40 Hz (1x rpm) could be observed. The most prominent vibration peak at 125 or 126 Hz (½ of BPF) was reported upon cavitation for testing condition 2 (Figure 4.3(b)) and testing condition 3 (Figure 4.3(c)). High vibration response peak at BPF was noted under testing condition 2 while the pump was cavitating. For normal operating condition, the vibration peak at 42 Hz (1x rpm) could be observed under testing condition 2 and testing condition 3.

Figure 4.3: Envelope Spectrum of Cavitation and Normal Operating Condition at Pump Casing (Front) in Axial Direction.
Envelope spectrums for all 3 testing conditions undertaken at various locations (casing, suction flange, discharge flange and bearing) are presented from Figure 4.4 to Figure 4.8.

Figure 4.4: Envelope Spectrum of Cavitation and Normal Operating Condition at Pump Casing in Radial Direction.
Figure 4.5: Envelope Spectrum of Cavitation and Normal Operating Condition at Pump Suction Flange in Axial Direction.
Figure 4.6: Envelope Spectrum of Cavitation and Normal Operating Condition at Pump Discharge Flange in Vertical Direction.

(c) Testing Condition 3

Figure 4.7: Envelope Spectrum of Cavitation and Normal Operating Condition at Pump Bearing in Horizontal Direction.

(a) Testing Condition 1

(b) Testing Condition 2

(c) Testing Condition 3
5. Consolidated Findings and Discussion

Comparing the cavitation and normal operating condition, there was a significant vibration amplitude increase observed at the frequency of ½ of BPF (either 120 Hz or 126 Hz) upon cavitation existence in the centrifugal pump. The amplitude increase was confirmed and consistent at most of measurement locations i.e. pump casing, pump suction & discharge flanges, and bearing. The half-order of sub-harmonics (½ of BPF) was always prominent, as evident in the envelope spectrum under cavitation condition. This was confirmed for 3 different testing conditions. The vibration amplitude at ½ of BPF was significantly lower during normal operating condition. Consistent with the experimental results of Ćudina (6), there was a discrete frequency tone within the audible noise spectra, which was at ½ of BPF and strongly dependent on the cavitation process and its development. The discrete frequency at half of BPF was therefore used to detect the cavitation. The possible explanation of the strong sub-harmonic (½ of BPF) during...
cavitation existence in the centrifugal pump was due to insufficient time for the bubbles to collapse completely before the end of the single cycle. It is consistent with the findings of Young (7). As the bubble was behaved in the transient characteristic, it grows or expands to at least double and often many times of their original size. The bubble then collapses violently, often disintegrating into a mass of smaller bubbles. In such cases, they may complete their collapse as transients at the subsequent maximum pressure. The half-order sub-harmonic (½ of BPF) may often appear in the short bursts separated by long intervals. The sub-harmonic component, and also the ultra-harmonics [at the frequency (2n+1) BPF/2] component are most likely at high drive frequencies where the bubbles responsible for them are small enough to remain in suspension in the liquid.

Since the bubble will have a resonant frequency and non-linear behaviour governed by the motion of the bubble, if the driving frequency (f) is a multiple n of the resonance frequency, the bubble may be excited at this resonance, which will be a sub-harmonic, f/2, f/3, f/4, etc. If the driving frequency is a sub-harmonic of the resonance frequency, then a higher harmonic of f, for example 2f, 3f, 4f, etc may be produced. Ultra-harmonics, for example 3f/2, 5f/2, 7f/2, may also be produced. As the bubbles were random in nature, both sub-harmonic and ultra-harmonic indeed could be appeared in the envelope spectrums. The half-order of sub-harmonic (½ of BPF) was however consistently appeared in most of the envelope spectrums.

The shock wave generated by a collapsing bubble and picked up by the accelerometer would in principle be recorded as an infinite series of harmonic components. In practice, however the higher frequency components might not reach the accelerometer, and with many bubbles emitting, the remainder will contribute to the general noise. This explains the raised floor noise could be seen in the envelope spectrum during cavitation condition.

Besides vibration response peaks at half of BPF was existence during cavitation condition, pertinent peaks at 40 Hz (1x rpm) and 240 Hz (BPF) could be observed in some of the envelope spectrums. During normal operating condition, the most dominant peak was observed at 40 Hz (1x rpm) at most of the measurement locations. It could be inferred that in the normal operating condition, the vibration energy was mainly contributed by the rotational speed. Comparing the vibration peak observed at the rotational speed frequency for both cavitation and normal operating condition, it was found that the vibration amplitude during cavitation was always significantly higher than normal operating condition.

There were some pertinent vibration peaks observed at 110 Hz and 191 Hz, which were associated with bearing damage. The 110 Hz component was apparently to be the outer race of the rolling element bearing frequency (BPFO) and the 190 Hz was identified as the inner race of the rolling element bearing frequency (BPFI). Cavitation had been observed causing the damage to the pump bearing. It caused the damage to the outer race of the bearing initially (proven by the vibration component found at 110 Hz). Furthermore along the experimental work, a high vibration peak at the frequency of 191 Hz could be observed in a few of the envelope spectrums undertaken at pump bearing even though under normal operating condition. Envelope spectrums undertaken at rolling element bearing were more complicated as it revealed the integrity of the bearing more than cavitation existence in the centrifugal pump. Many sidebands could therefore be observed in the envelope spectrum undertaken at the pump bearing. This enveloping method has been proven useful for bearing fault detection as bearing also generate high frequency vibration at the early stage of the fault.

Envelope analysis was proven to be successful in detecting cavitation existence in the centrifugal pump. All the envelope spectrums were undertaken at the frequency band-pass filter range of 5 kHz to 40 kHz. It is worthy to mention that the bubble collapses in a very short time (i.e. < 0.003 s), and thus generates very high pressure pulse, high frequency
vibration and noise. Acceleration enveloping offers a facility to filter out the low frequency. The envelope spectrums undertaken were therefore generated from the high vibration frequency, which were greater than 5kHz. The measurement location of the cavitation detection was indeed important. It was found that pump casing, suction flange and discharge flange were suitable as a measurement location to detect cavitation. Vibration measurement at the centrifugal pump casing (measured in axial direction) seems to be the best location concluded from the experimental work. Measurement location of pump bearing was found not a suitable location to detect cavitation existence in the centrifugal pump through this envelope analysis.

Prior to cavitation (A1-A6 or B1-B6 or C1-C6), the envelope spectrum undertaken while the suction pressure was being decreased was approximately in the same range. No specific trend of the envelope spectrums either in ½ of BPF, BPF or rotational speed was observed during the suction pressure being decreased (A1-A6). Upon cavitation, there was a significantly increase of vibration level in the envelope spectrum as being compared in the experimental results. This finding was consistent for all the measurement locations and all 3 testing conditions.

6. Conclusion

Envelope analysis was proven useful in detecting cavitation over the 3 testing conditions. During the normal operating condition, vibration peak synchronous to rotational speed was more pronounced. It was however during cavitation condition, the half order sub-harmonic vibration component was clearly evident in the envelope spectrums undertaken at all measurement locations except at the pump bearing. The possible explanation of the strong sub-harmonic (½ of BPF) during cavitation existence in the centrifugal pump was due to insufficient time for the bubbles to collapse completely before the end of the single cycle. Bearing related frequencies such as outer ball passing frequency (BPFO) and inner ball passing frequency (BPFI) could be observed in some of the envelope spectrum especially at pump bearing. This implied the damage of the bearing due to cavitation.

References