Al-Braik, Abdulrahman, Hamomd, Osama, Gu, Fengshou and Ball, Andrew

Diagnosis of Impeller Faults in a Centrifugal Pump Using Vibration Signals

Diagnosis of Impeller Faults in a Centrifugal Pump Based on Spectrum Analysis of Vibration Signals

Abdulrahman Al-braik, Osama Hamomd, F. Gu and A. D. Ball
Centre for Efficiency and Performance Engineering, University of Huddersfield,
HD1 3HD, UK
albraik@live.co.uk

Abstract

Centrifugal pumps are widely used in many critical applications. To ensure the safety and high performance of pump operations vibration techniques are generally used for condition monitoring. However it has noticed that less research has paid to developing monitoring approaches to the faults on impellers which is core part and subject to constant erosions. This paper focus on the studies of vibration responses to the incipient van tip faults on impellers and developing corresponding features to detect and diagnose this faults. It has found that the spectral components from flow turbulence are predominant in the high frequency range above 1kHz, which are shown less changes due to defects on the exit tip of impellers. On the other hand the discrete components caused by the interaction of flow, impeller and casing show more definitive changes due to the defects. In particular the amplitudes at vane passing frequency and the higher order harmonics at shaft frequency can be effective features for the detection and diagnosis of the fault severity.

1 Introduction

Centrifugal pumps are used in many important industries such as petroleum refining process, petrochemical plant and power stations. Considering the criticality of these applications, the monitoring of the centrifugal pumps is necessary to ensure high-performance safety operations of pumps. Therefore, many studies have been conducted in recent years with more advanced data analysis methods applied to the vibration of the pump.

Berli Kamiel et al [2] proposed to develop a framework for impeller fault detection using multi sensor data collection and principal component analysis. Vibration signatures of normal and faulty impellers were collected from a Spectra Quest Machinery Fault Simulator. The impeller fault was introduced by cutting two slots on the blade at two locations in the middle section of the blade, and four accelerometers were mounted on the pump on the volute case. Four statistical features (kurtosis, RMS, skewness, and variance) were extracted from time data which was previously separated into frequency bands or octaves.

Rafik ZOUARI et al [4] described a diagnosis system for centrifugal pumps that was developed in the framework of pump maintenance project using use neuro-fuzzy models. The system is based on vibration measurements, signal pre-processing and classification with pattern recognition approaches for detecting faults including misalignment, cavitation, partial flow, and air injection.

Saeid Farokhzad [5] presented an adaptive network fuzzy inference system (ANFIS) to diagnose the fault type of the pump. The pump conditions were considered to be healthy, broken impeller, worn impeller, leakage and cavitation. These features are extracted from vibration signals using the FFT technique. The features were fed into an adaptive neurofuzzy inference system as input vectors. Performance of the system was validated by applying the testing data set to the trained ANFIS model.

The works mentioned above are mainly based on statistical characteristics of vibration signals for detection and diagnosis. As these statistical characteristics are highly depends on the design features and applications of different pumps, these approaches may be lack of generalisation. In addition, the results are often cannot be explained by engineering sense, making it difficult to convince the presence of faults at early. To overcome the shortcomings of the methods this study focuses on developing detection and diagnostics using more deterministic features such as the vibration components from pressure pulsations. In addition, it focuses on the diagnosis of early faults on impellers which are the core parts of a centrifugal pump and subject to different erosions including evitable cavitation and turbulence.

2 Understanding of Vibration in a Centrifugal Pump

There are many vibration sources in a centrifugal pump. They may be understood based on two general categories: hydraulic excitations and mechanical excitations in order to analyse vibration responses for developing diagnostic approaches.

2.1 Hydraulic Sources-pressure pulsations

In centrifugal pumps, a significant amount of vibration is due to hydraulic forces [10]. Hydraulic forces are excitations due to pulsations from the flow interaction with impeller vanes, flow turbulences, cavitation and hydraulic instability [11].

2.1.1 Interaction between impeller flow and volute casing

Centrifugal pumps transport fluids by the conversion of rotational kinetic energy to the hydrodynamic energy of the fluid flow. The fluid enters the pump impeller along or near to the rotating axis and is accelerated by the impeller, flowing radially outward into a diffuser or volute chamber (casing), from where it exits. Because the flow interacts inevitably with impeller blades and with the stationary volute chambers, the pressure of fluid will pulsate largely with the structure of the impeller. In particular, the pulsation rate will be correlated with the vane numbers. In particular this characteristic frequency is named as vane-passing frequencies:

$$f_{vp} = kz f_r$$

where k is the harmonics number, z is the vane number and f_r is pump speed in Hz. Moreover, the amplitude of this pressure pulsation is mammal when a pump operates at its best efficiency points(BEP) at which the flow velocity matches the vane angle so that the flow produces the least interactions to the impeller. On other hand, any operations off the BEP will cause mismatch between the fluid velocity angles and the vane angles in the impeller and result in high pressure pulsation and vibration. Based on these characteristics effective features can be developed for the purpose of impeller fault diagnosis.

2.1.2 Flow Turbulence

Flow turbulence is also inevitable phenomena occurring in centrifugal pumps. It induces vortices and wakes in the clearance space between the impeller vane tips and the diffuser or volute lips, which in turn produces pressure fluctuations or pulsations leading to vibration. The frequency of turbulence induced vibration is predicted by

$$f_w = Sn\, V/D$$

where V is the velocity of turbulence flow, Sn is the dimensionless Strouhl number with a value range from 0.2 to 0.5 and D is the characteristic dimension of the obstruction. As the flow velocities are very diversity, this type of pulsation could produce vibration over a wide frequency range.

In particular, the recirculation flow near either the suction or the discharge tips of the vanes impeller causes significant turbulences. These high velocity flows will create vortices. Collapsing of the vortices produces noise and cavitation at both the suction and the discharge of the pump. When a centrifugal pump is operated at a very low flow rate, recirculation occurs within the impeller, and it surges at the natural frequency of the system [14,15].

2.1.3 Due to Cavitation

The formation of cavitation in centrifugal pump is one of the main concerns affecting pump performance. Cavitation is a fundamental factor which affects the reliability and operability of the pump[16], which is caused by the sudden implosion of vapour bubbles in low pressure regions as they move into high pressure zones in the pump housing occurring the hydraulic instability [17]. Cavitation can lead to erosion damage, vibration, hydraulic instability and performance deterioration by periodic inception, growth, depletion of vapor bubbles. Particularly, cavitation reduces pump efficiency and causes pressure head damage [18].

2.2 *Mechanical Sources*

The mechanical causes of vibrations include mechanical unbalance, misalignment and bearing failures.

2.2.1 Unbalance

Unbalance occurs when the central axis is not parallel to the axis of rotation. Due to the unbalance in the pump impeller, vibration takes place and leads to reduce in fluid velocity and local pressure which may cause an undesirable turbulence. Hence, to remove the unbalance in rotor is necessary [7]. Unbalance typically induces vibrations at 1X of running speed f_r or shaft frequency.

2.2.2 Misalignment

Misalignment is one of the common causes in the pump. Misalignment is normally well-known by two types: offset and angular. Offset is the amount that the two centrelines are offset from each other (i.e. Pump and motor). Angular is the differential crossing angle that the two shaft centreline make when projected to each other. Misalignment typically causes vibrations at twice running speed $2 \times f_r$ and sometimes misalignment load may cause higher harmonics[8].

2.2.3 Bearing Failure

Bearing problems mainly either through contamination of the bearing lubricants by another liquid, or solid particles or because of high heat, which is caused by an overload on the bearing. Once the bearing is faulty the vibration may show additional components at the fractional frequencies $x \times f_r$ of the shaft frequency.

3 Experimental Setup

The pump test rig consists of a centrifugal pump, electric motor and close-loop piping water system for water circulation, which is schematized in Fig. 1. The pump model is a F32/200A series standardized to DIN 24255. It is a single suction, single stage, end/top discharge, closed impeller and closed-coupled centrifugal pump, which can deliver water at a rate of 250l/min at a head of up to 55m. A variable-speed electric motor is used to control the speed of the centrifugal pump by adjusting the supply to the three phase induction motor of 4kWw at 2900rpm.

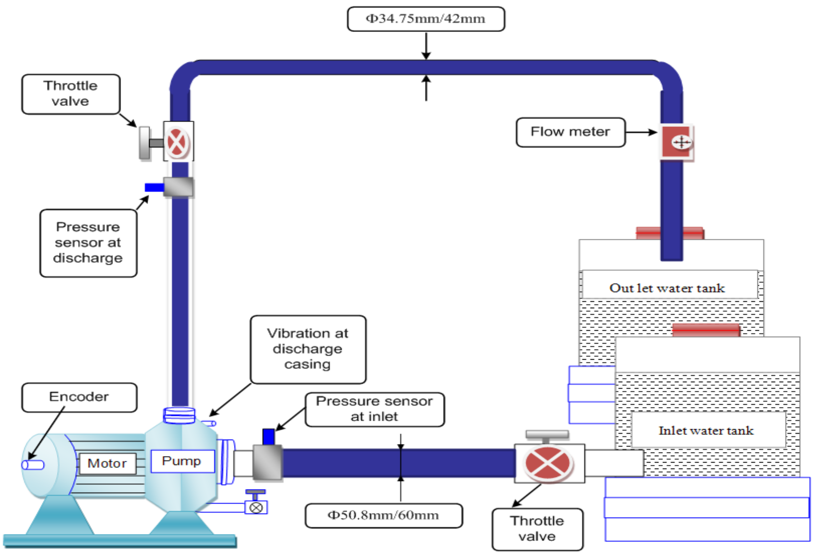

Figure 1. Schematic of test system

As shown in Fig. 1 the vibration of pump is measured at the exit port of the pump casing with an accelerometer. The specification of the accelerometer used to measure the vibration is given in Table 1. In addition, the rotational speed of the pump is measured by a shaft encoder at the free end of the motor. A flow sensor was installed in the discharge line for flow rate measurement. Two pressure sensors are installed in the suction and discharge lines respectively for pump delivery head measurement. All of these measurements are sampled by a high speed data acquisition system at a rate 96kHz and 24bit data resolution.

Table 1. Specification of the accelerometer.

Type	Accelerometer (piezoelectric)
Model	YD3-8131
Frequency range	2Hz – 15kHz

Sensitive	1.51mv/ms-2
Range	<2000ms-2
Temperature range	< 250°C

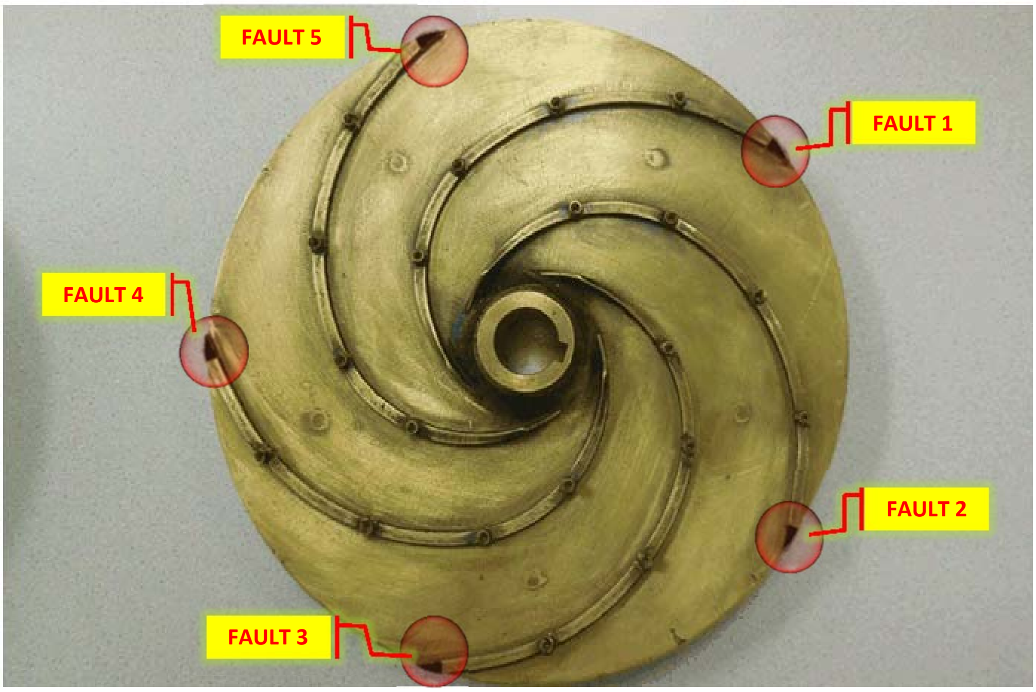

Figure 2 An illustration of van tip fault induced to an impeller

Six tests were performed in this experimental study. The first one is the baseline test and the rests are for five different degrees of defects vane tips. For each test the vibration is measured at the fixed motor speed of 2900rpm but with seven increments of flow rates of 50, 100, 150, 200, 250 300 and 340 l/min.

The photograph in Figure 2 shows the internal construction of a closed type impeller. In the figure it shows the location of the defect on the exit tip of each vane which is created by cutting away 3 mm along the length direction one vane by one vane during the test. After the baseline test, five tests were taken for five different fault severities respectively in which the first test is under the defect of only one tip, the second for two tips and so on. This then allows five digress of vane damage to be explored for evaluation of accuracy of vibration based diagnosis. In addition, for the ease of discussion these test cases are denoted as BL, F1, F2, F3, F4 and F5 respectively.

4 Results and Discussion

To understand the vibration characteristics and define an effective diagnostic feature accordingly for the different fault cases. Vibration signals are analysed with both normal spectrum representations and then with bispectrum patterns. The former may gains a general quantitative understanding of the pump vibration responses such as that discussed analytically in section 2 and the latter allows a more detailed examination of particular components such as the vane passing vibration for accurate diagnosis.

5.1 Spectrum characterises in the low frequency range

As understood in section 2, the vibration responses from pumps can spread over a wide frequency range. To examine the details of the responses its spectrum is studied in a flow frequency range from 0 to 1kHz and 1kHz to 10kHz.

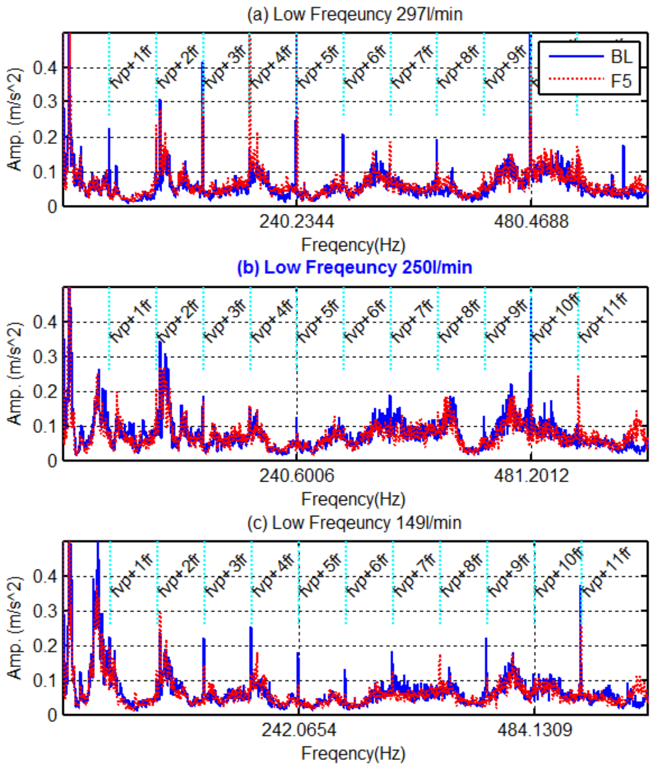

Figure 3 Vibration spectrum in the low frequency range

Figure 3 shows vibration spectrum in a low frequency under three typical flow rates: above the BEP flow BEP flow and below BEP flow for the baseline and the defect on five vanes. It can be observed that the vibration spectrum exhibit clear broadband due to flow turbulence and visible discrete components due to the interactions between vane and flow. The broadband amplitudes show higher amplitude on the BEP operation while the discrete components are more distinctive for the off-BEP operation, showing that more pressure pulsations due to interaction effects whereas more turbulent interaction at the BEP. In addition the discrete components appear not only at the vane-passing frequencies of 240.6Hz and 181.2Hz but also at the shaft frequency 48.1Hz and its harmonics. The shaft related commoners, especially at its harmonics may indicate the asymmetry between vanes and hence could be useful for reveal the faults.

However, the difference is not very clear between the defect case and the baseline in either the broadband components or the discrete components. In addition considering that it is difficult to give an accurate of the wideband components, only discrete components are extracted at each shaft frequency and examined in detail. Figure 4 shows three typical components against different flow rate and the impeller cases. The 1X of Fig. 4 (a) shows a similar amplitude throughout different flow rates, indicating it is relating more to the problems of unbalance and misalignments. In addition, it has no connection with the expected behaviour caused by the defects.

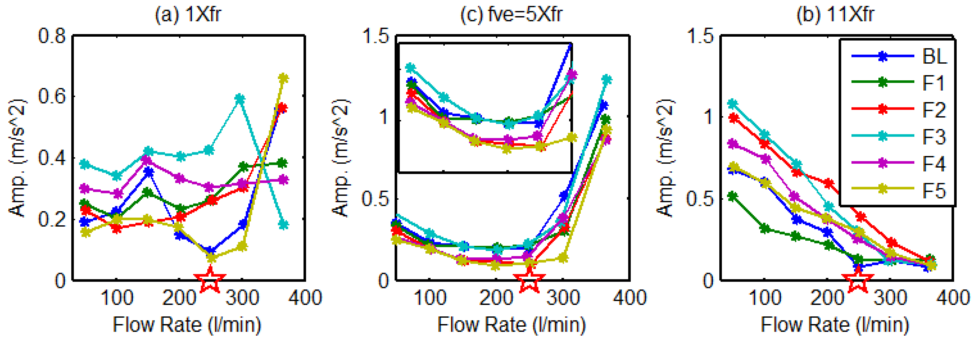

Figure 4 Spectral amplitudes of discrete components for different fault cases

On the other hand, the component at the vane passing frequency shows a good agreement with that the vibration is the lowest at BEP. In addition, the amplitudes for F3, F4 and F5 are lower than the baseline and F1 and F2 is close to the baseline, showing that the interaction is lower due to the higher recirculation caused by the faults. Therefore, this component is more correlated to fault cases induced. However, it is not possible to separate the F1 and F3 from the baseline. In addition it may cause in adequate diagnosis for F2.

In the meantime, the amplitude behaviour shows more consistent with the fault cases in the flow range lower than that of BEP. It shows that the defects cause more vibration. In particular, F3 is the most asymmetric defect. So it causes the highest vibration. F2 and F4 the second one and their vibration amplitudes show the second high. On the other hand F1 and F5 are the lowest asymmetric defects and hence their amplitude is the lowest and close to that of baseline. However, the amplitude for all defect cases around BEP, concerned particularly in applications, is not very consistent. Especially, the amplitude for F2 is higher than that F3, F4 and F5.

In general, the discrete components at f_{vp} and $11\times f_r$ can provide a large quantity of information for diagnosing the vane defects but they are not sufficiently accurate because of the influences of wideband random components.

5.2 Spectrum characterises in the high frequency range

Figure 5 shows vibration spectrum in a higher frequency range under three typical flow rates: above the BEP flow BEP flow and below BEP flow for the baseline and the defect on five vanes. It can be seen that the spectrum exhibits typical wideband feature. In addition, there are several frequency ranges showing higher amplitude due to the effects of resonances in the flow or casing structures. Moreover, the amplitude in the frequency range from 4.5kHz to 6kHz are distinctively high for the higher flow above BEP, showing significant influences of cavitation.

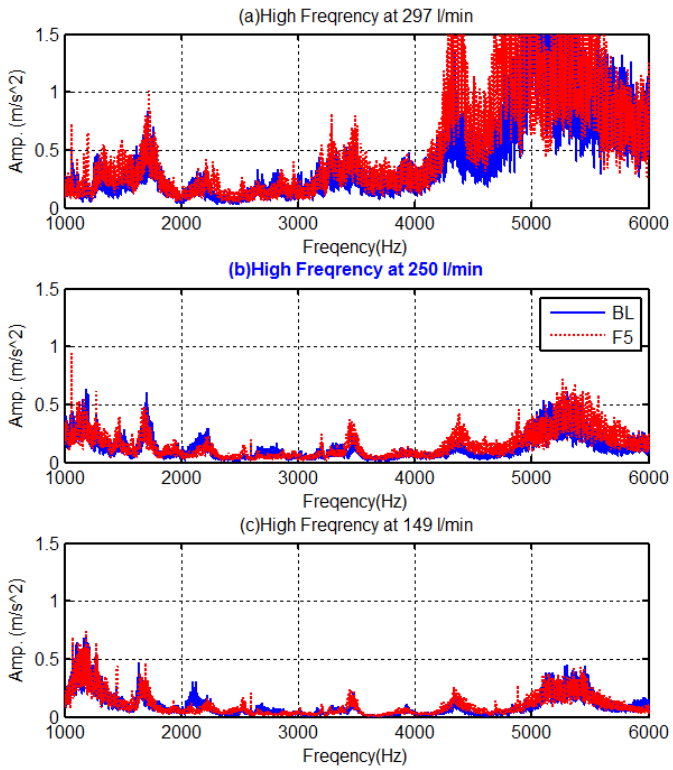

Figure 5 Vibration spectrum in the high frequency range

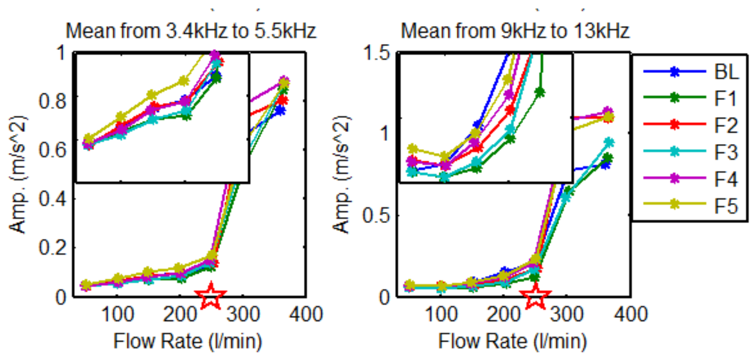

Figure 6 Mean amplitude

Comparing the spectral difference between the baseline and F5, it has identified two potential frequency ranges in which the amplitude increases or decreases monophonically with defect degrees. In addition, the selection of these two ranges because they contain less influence from noise such as the components from the variable frequency drive but mainly that due to turbulence effects. Figure 6 shows the spectral amplitudes averaged in the two ranges. The amplitude shows an increasing trend with the flow rates, which is agree with the prediction of turbulence induced vibrations. Unfortunately, the difference between different defect cases cannot be differentiated to be consistent with the fault severity induced. This may be due to that the changes due to defects are influenced by the strong turbulence vibration of the inherent flow. Therefore, it is very difficult to use the high frequency information for diagnosing the fault.

5 Conclusions

Based on a general understanding of vibration characteristics of pumps, experimental studies have been carried out on a centrifugal pump for developing effective diagnosis features for incipient impeller defects. It has found that the spectral components from flow turbulence are predominant in the high frequency range above 1kHz, which are shown less changes due to defects on the exit tip of impellers. On the other hand the discrete components caused by the interaction of flow, impeller and casing show more definitive changes due to the defects. In particular the amplitudes at vane passing frequency and the higher order harmonics at shaft frequency can be effective features for the detection and diagnosis of the fault severity. However, because of the random noise of flow turbulence in the low frequency range, one of the five fault cases cannot be diagnosed very accurately. Further study will focus on suppressing the noise due to turbulence in the low frequency range to achieve a full diagnosis results.

References

1. M. G. Patel and A. V. Doshi, Effect of Empeller Blade Exit Angle on the Performance of Centrifugal Pump, (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 3, Issue 1, January 2013).
2. Berli Kamiel, Gareth Forbes, Rodney Entwistle, Ilyas Mazhar2 and Ian Howard2, Impeller Fault Detection for a Centrifugal Pump Using Principal Component Analysis of Time Domain Vibration Features, Department of Mechanical Engineering, Universitiey Muhammadiyah Yogyakarta, Indonesia
3. Sergeuei Timouchef and Jean Tourret, Numerical Simulation of BPF Pressure Pulsation Field in Centrifugal Pump, proceedings of the 19th international pump users symposium.
4. Rafik ZOUARI, Sophie SIEG-ZIEBA, Menad SIDAHMED, Fault Detection System For Centrifugal Pumps Using Neural Networks And Neuro-Fuzzy techniques, Surveillance 5 Cetim Senlis 11-13 October, 2004.
5. Saeid Farokhzad ,Vibration Based Fault Detection of Centrifugal Pump by Fast Fourier Transform and Adaptive Neuro-Fuzzy Inference System, Journal of Mechanical Engineering and Technology, Dec. 2013.
6. William D. Marscher, P.E, an end user,s guide to pump vibration, Mechanical solutions, Inc., 11 Apollo Drive, whippani NJ 07891.
7. Sanay Taneja, Effect Of Unbalance On Performance Of Centrifugal Pump, International Journal Of Scientific & Technology Research Volume 2, Issue 8, August 2013.
8. Eric J. Olson, Centrifugal Pump Vibration Diagnostics, Mechanical Solutions, Inc. 11 Apollo Drive, whippani NJ 07891.
9. Kristoffer K. McKee, Gareth Forbes, Ilyas Mazhar, Rodney Entwistle and Ian Howard, review of major centrifugal pump failure modes withapplication to the water supply and sewerage industries, ICOMS Asset Management Conference, May 16 2011.
10. Ravindra Birajdar , Rajashri Patil and Kedar Khanzode , Vibration And Noise In Centrifugal Pumps - Sources And Diagnosis Methods, Paper Ref: S1163_P0437, 3rd

International Conference on Integrity, Reliability and Failure, Porto/Portugal, 20-24 July 2009.

11. Stefan Florjancic and Arno Frei, Dynamic Loading in Pumps – Causes for Vibration, www.Turbolab.tamo.edu, accessed 21/12/2013.
12. Fred L. Robinett and Thomas Kaiser, Vane Pass Fabrication-Source, Assesment and Corrosion-A Practical Guide for Centrifugal Pumps. Proceedings of the 16th International Pump Users Symposium.
13. Mark A. Corbo and Charles F. Stearns, Practical Design Against Pump Pulsation, Proceedings of the 22th international Pump Users Symposium (2005).
14. Warren H. Fraser, Flow Recirculation in Centrifugal Pumps, Proceeding of the ninth Turbomachinery Symposium.
15. Pump-Cavitation, www.enggcyclopedia, date of access 01/04/2014.
16. Donald P. Sloteman, Cavitation in High Energy Pump-Detection and assessment Damage potential, Curtiss-Wright, Electro-Mechanical Corporation, Phillipsburg, New Jersey
17. W.M. Koné, D. Soro, B. Dro, K. Yao and K. Kamanzi. Detection of Cavitation in Centrifugal Pumps, Australian Journal of Basic and Applied Sciences, 5(10): 1260-1267, 2011.
18. Quangnha Thai and Changjin Lee, The cavitation behavior with short length blades in centrifugal pump, Journal of Mechanical Science and Technology 24 (10) (2010) 2007~2016, 2010.