Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 9 (7): 1317-1323, 2009
ISSN 1812-5654

The Application of Laser Velocity Meter in Detecting Incipient Cavitation and Measurement its Intensity, Inside Axial Flow Pumps

H.A. Tash, M. Sadeghi, M.T. Shervanitabar and M.M. Ettefagh
Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran

Abstract: Though the cavitation as a damaging phenomenon of hydraulic devices, has been drawing the interest of many researchers, almost very few investigations have been done on the cavitation measurement inside axial flow pumps. The present study is one of the leading ones which consider this phenomenon inside this widely used type of pumps. Oscillations of the structure of the pump were used to measure the cavitation. An average energy method for identification cavitation occurrence and measurement its intensity has been developed. This is called Logarithmic Cavitation Intensity (LCI). A statistical analysis was undertaken in a both time and frequency domains and the LCI was proved as a proper criterion for defining the cavitation intensity. Though being very robust, the introduced method is very simple and does not require time consuming calculations. This causes LCI method to be feasible by simple hardware with low sampling frequency, resulting in reducing the computational time as well as hardware complexity and cost.

Key words: Cavitation, axial flow pump, logarithmic cavitation intensity, energy method

INTRODUCTION

Cavitation is rapid formation and collapse of vapor bubbles, some times occurs within pumps or other hydraulic devices. This malfunction can be extremely destructive to the pump. Cavitation can cause pitting of impeller, impeller vanes and pump casing. At the other hand, the pump efficiency will decrease significantly during cavitation (Gulich, 2008). Therefore, cavitation in pumps, as an unacceptable phenomenon, should by all means be avoided. To do this, one has to know the inception of cavitation and its intensity within pump, especially for pumps working in industrial environments.

Cavitation within water pumps has been the subject of numerous studies. According to the available literatures, there are two different approaches to detect the onset of cavitation in a liquid:

Numerical modeling: It is often used to predict the onset of cavitation of a single bubble and rarely within a pump. There are some well-known models, which can be used in describing the phenomena and behavior of cavitation cores (Tsudaa and Takagib, 2008; Zhang *et al*., 2008b). However, there is no exact algorithm to calculate the noise due to cavitation at the different operating conditions of a pump.

Engineering methods: The exact value of cavitation noise can be obtained by one of the available engineering methods. The engineering methods which have been utilized until now are:

- **Determination of the Net Positive Suction Head (NPSH) at constant pump speed and flow rate:** According to ISO standard, drop in the total delivery head is a good criterion to identify fully developed cavitation inside a pump (Europump, 1999)
- **Visualization of flow:** Using a transparent model casing and often a stroboscopic, visualization of cavitation is possible. This method is suitable for a single bubble and for high-powered pumps (Lee *et al*., 2008; Zhang *et al*., 2008a)
- **Paint erosion testing:** This method is based on painting the impeller blades and shrouds and observation of the cavitation erosion by evidence of the removal of the paint. Its application is good in combination with the NPSH test, which shows if the cavitation occurred within the pump or not (Gulich, 2008)
- **Measurement of the static pressure within the flow:** With this method, the onset of the cavitation cores is determined indirectly by comparison of the measured static pressure and the vapor pressure at a given temperature of the flow (Lee *et al*., 2008)

Corresponding Author: Hadi Arjmandi Tash, Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran
Tel: 0098 9144196979

- **Measurement of the vibration of structure:** The implosion of vapor-filled zones (bubbles) generates pressure pulsations which excite structure vibrations; by mounting a transducer on the pump body, the cavitation and its intensity can be monitored. The measured signal may be contaminated and corrupted by background noise, such as that of aerodynamical, mechanical and electromagnetic origins, which attenuate or amplify the measured signal (Futakawa *et al*., 2008; Farkas and Pandula, 2006)
- **Measurement of the sound pressure:** Cavitation produces broadband high-frequent noise. This noise is emitted when the cavities collapse violently and when the high pressure peaks are generated. Using sensitive microphones and sound level meters, incipient cavitation can be identified (Karpiouk *et al*., 2008; Alfayez and Dyson, 2005; Hodnett and Zeqiri, 2008)
- **Analysis of pump driver input variables:** Measurement of electrical characteristics of the pump electromotor (current and voltage for example) some times gives variable information to monitor cavitation inside pump

When detecting cavitation from an operating machine, environmental disturbances make the indirect measurements difficult. Indirect measurement methods will especially be useful if the measured data from non-cavitation circumstances are available.

Since, the cavitation in pump was taken into consideration, most cavitation detection studies have been concentrated in cavitation inside centrifugal pumps (Alfayez and Dyson, 2005; Al-Hashmi *et al*., 2004; Hattori and Kishimoto, 2008). Though the axial flow pumps are extremely used in application and industry, much less studies have been reported about cavitation in these types of pumps. It seems that the present study is one of the leading experiments, done in the measurement of cavitation in an axial flow pump.

This study which can be classified into the engineering methods category, offers a simple and yet novel technique to detect cavitation and presents an index to show its intensity. A suitable laser velocity probe was used to capture the oscillations of the tested pump structure. The data obtained from this sensor were analyzed by a developed Energy Method, both in the time and frequency domains. The output of this modeling was assigned to an index, named by LCI. More illustrations showed that the LCI is capable to identify the occurrence and quantify the intensity of cavitation within pumps. The results also demonstrate that the proposed method is able to detect cavitation by a simple hardware with low sampling frequency. This character leads to reduction the computation time as well as hardware complexity and cost.

CAVITATION

Cavitation may appear to be a problem in fluid power systems. It affects fluid power systems and components in various ways, which are usually undesirable. The severity of the effects of cavitation varies as a function of a machine's power. Figure 1 shows an impeller that has been severely damaged by cavitation.

Cavitation is usually divided into two classes of behavior: inertial (or transient) cavitation and non-inertial cavitation. Inertial cavitation is the process when a void or bubble in a liquid rapidly collapses and produces a shock wave (Brujan *et al*., 2008). Such cavitation often occurs in pumps, propellers, impellers and in the vascular tissues of plants. Non-inertial cavitation is the process where a bubble in a fluid is forced to oscillate in size or shape due to some form of energy input, such as an acoustic field (Suslick and Flannigan, 2008).

Within a pump, the flow area at the eye of the pump impeller is usually smaller than either the flow area of the pump suction piping or the flow area through the impeller vanes. At the eye of a pump, the decrease in flow area results in an increase in flow velocity accompanied by a decrease in its pressure. The greater the pump flow rate, the greater the pressure drop. When the local pressure falls below the saturation pressure of the fluid, the liquid may flash to vapor. Any vapor bubbles formed by the pressure drop at the eye of the impeller are swept along the impeller vanes by the flow of the fluid. When the bubbles enter a region where local pressure is greater than the saturation pressure farther out the impeller vane, the vapor bubbles abruptly collapse. This process of the formation and subsequent collapse of vapor bubbles in a pump is called cavitation (France and Michel, 2005).

Fig. 1: A cavitation damaged impeller

Cavitation in a pump has a significant effect on pump performance. It degrades the performance of the pump which leads to fluctuation in the flow rate and discharge pressure. Cavitation can also be destructive to the pump internal components. If a pump cavitates, collapse of vapor bubbles will cause a physical shock to the leading edge of its impeller vane. This shock will create small pits on this area of the impeller vane. Each individual pit is microscopic in size, but the cumulative effect of millions of these pits, over a long period of time can eventually destroy the pump impeller (Zheng *et al*., 2008; Xu *et al*., 2005; Guogang *et al*., 2008; Hattori and Kishimoto, 2008). Cavitation can also cause excessive pump vibration, which could damage the pump bearings, wearing rings and seals. To avoid the cavitation, the pressure of the fluid at all points within the pump must remain above the fluid saturation pressure. The existence of cavitation is often very difficult to detect because cavitation occurs typically at locations where the access for measuring instruments is limited.

THE DOPPLER EFFECT (Maulik, 2005)

The doppler effect, named after Christian Doppler, is the change in frequency and wavelength of a wave which is perceived by an observer moving relative to the source of the wave. A stationary light source emits a continuous light wave with the frequency f and the wavelength λ. A wave train with the length λ passes a stationary observer in the time $T = 1/f$. If in contrast the observer moves away from the light source at the speed v, then the wave train needs a slightly longer time T', to pass the observer. The total distance the wave travel in the time T includes the distance λ of the observed wave train and also the distance v, T' traveled by the moved observer in the time T'. For the moving observer, the wave vibration has the cycle duration T' and because $f' = 1/T'$ and $\lambda = c/f$, this then results in:

$$(c-v)/f' = c/f \tag{1}$$

and thus the frequency f' to:

$$f' = f\,(c-v)/c = f\,(1-v/c) \tag{2}$$

Therefore, if the observer moves away from the light source (v>0), then the light frequency will be shifted to smaller values (red shift) and if he moves towards the light source (v<0), then an increased frequency will be measured (blue shift). Figure 2 schematically shows this effect. The above analysis is an approximation for small velocities in comparison to the speed of light which is fulfilled very well for practically all technically relevant velocities and is the base of laser velocity probes.

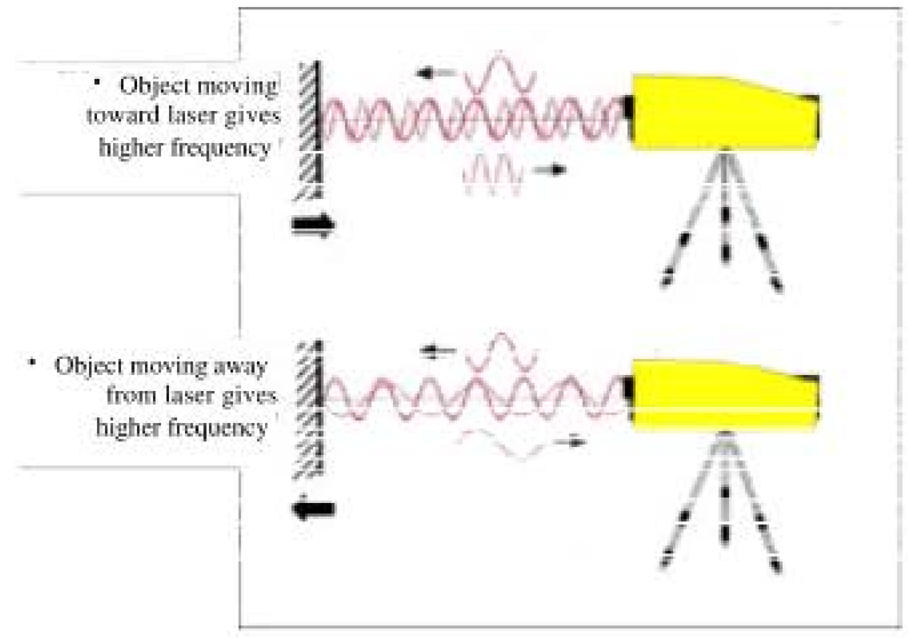

Fig. 2: Application of Doppler effect in laser velocity probes

EXPERIMENTAL SET-UP AND MEASUREMENTS

An experimental axial flow pump was chosen for the experiments. The pump was a single volute design with a 5-vane closed-face impeller. The impeller and shaft were supported by two rolling element bearings and were coupled to a 5.6 kW motor with a relatively flexible coupling. The motor was driven directly from a 480 V, 60 Hz source. This experimental pump has been designed and well adapted to analyze the cavitation phenomenon. Its vanes angle was changeable by which cavitation with different intensity levels could be created inside. At the other hand, it had a transparent impeller casing through which and utilizing a stroboscopic light, the cavitation intensity within the pump case could be identified. This pump also was well equipped with suitable gages to determine NPSH and its drop in cavitation condition according to ISO standard. During the tests, the pumping loop was supplied with water from a 5000 L tank. The loop could support up to 50 L sec^{-1} flow rates. A stature of the utilized experimental pump and its equipments is shown in Fig. 3.

In all test cases a Laser Doppler Velocity Probe was used to measure velocity of the outside body of the water pump. A frequency of 50 kHz was chosen as the sampling frequency of the used A/D hardware. If a much higher sampling frequency was used then there would be more data to be handled, more memory would be required and the computation time would be longer. In practice, in order to be sure of having no aliasing, an analogue anti-aliasing low-pass filter with a cut-off frequency less than half of the sampling frequency was used before sampling. At the other hand, the window effect is a common problem in spectra analysis. It has been found (Gao *et al*., 1993) that the Hamming window is the best choice for the spectra analysis.

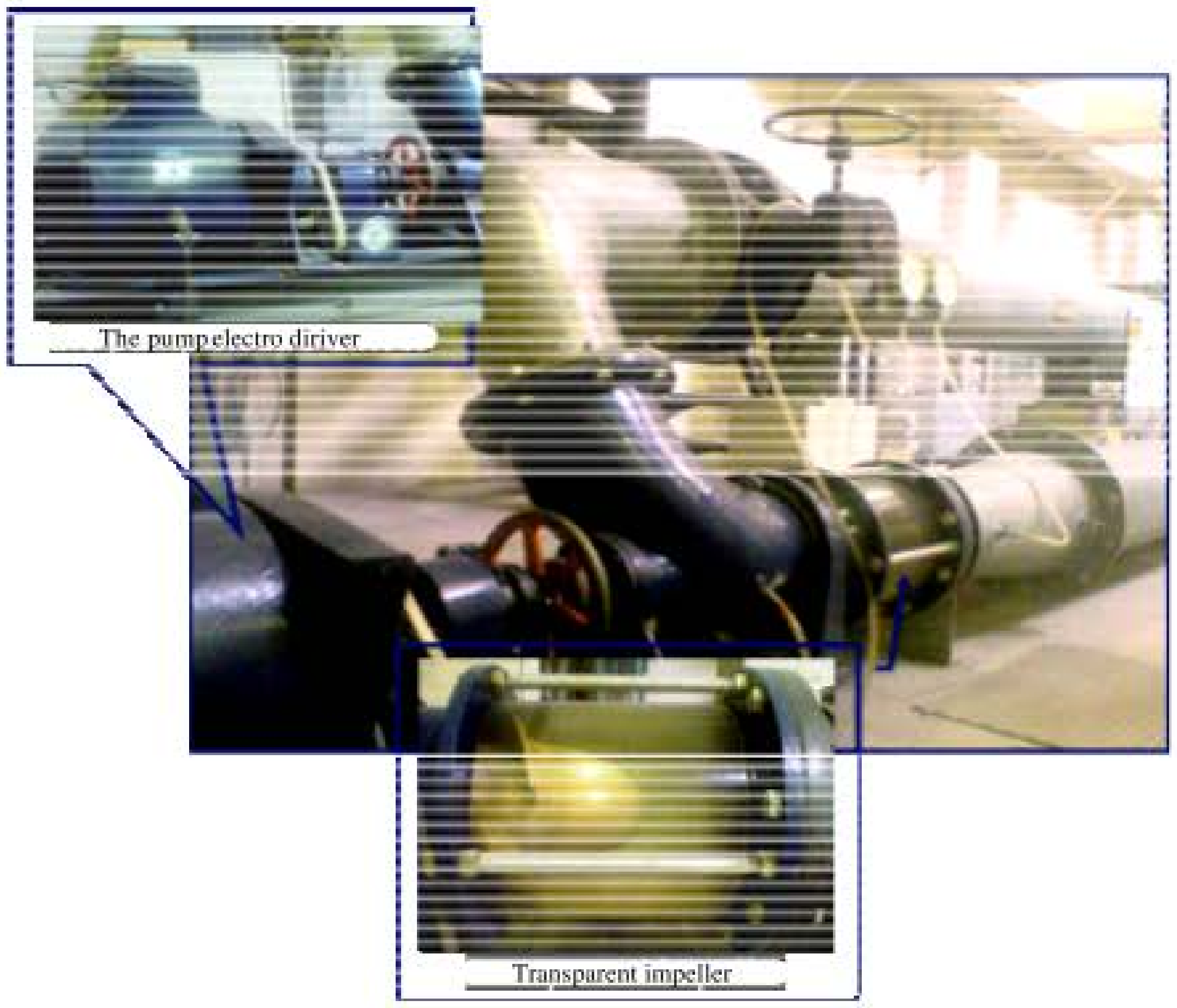

Fig. 3: The utilized experimental pump and pumping loop

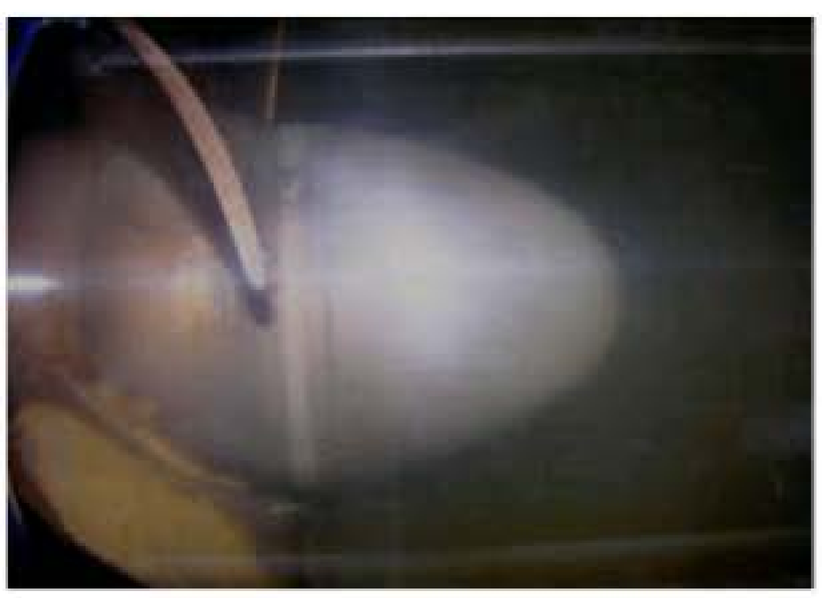

Fig. 4: Cavitation free case. The vanes angle was set to 20°

Fig. 5: First stage of cavitation. Increasing the vane angle by 2° caused the first cavitation bubbles create around the impeller vanes

Fig. 6: Second stage of cavitation. The vanes angle was increased by 2°. The cavitation bubbles extended and a mild cavitation noise was hearing. The pump efficiency relatively began to drop

The data acquisition processes executed in 5 different intensity levels of cavitation; cavitation free stage and four high and higher cavitation intensities. At each level, the pump was run at a constant speed of 1500 rpm for a sufficiently long time to bring the flow state to an equilibrium. Then data collection step initiated and sufficient data were saved. The vane angle then slowly was altered and the cavitation with other intensity level occurred in the pump. Figure 4-8 show the different stages of experiments.

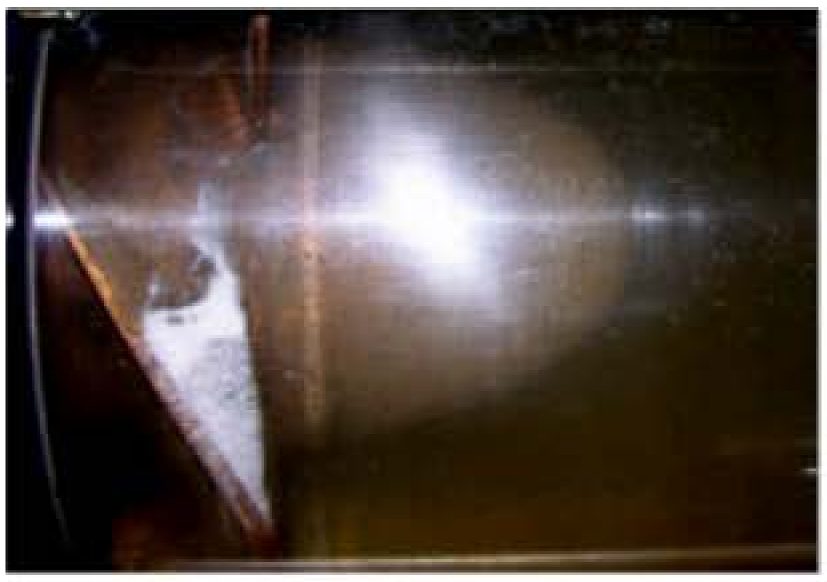

Fig. 7: Third stage of cavitation. The vanes angle was set at around 26°. The cavitation extended more and more and its noise increased

Fig. 8: Final stage of experiments which was related to vanes angle of 29°. The cavitation bubbles not only enclosed the vanes, but extended to whole impeller case also. A severe cavitation noise similar to knocking was hearing and the pump efficiency fell dramatically

ANALYSIS AND RESULTS

The approach of this study to quantify cavitation intensity is shown in Fig. 9. Having shown that the body vibrations are usually made up of several frequencies, an appropriate description of cavitation intensity is the average energy. The advantage of using the average energy method is its equivalence in the frequency and in the time domains. The equation of the average energy in terms of the spectra data is:

$$\text{Average energy} = \sum X^2(k) \quad (3)$$

and in the time domain:

$$\text{Average energy} = \frac{1}{N}\sum_{n=0}^{N-1} x^2(n) \quad (4)$$

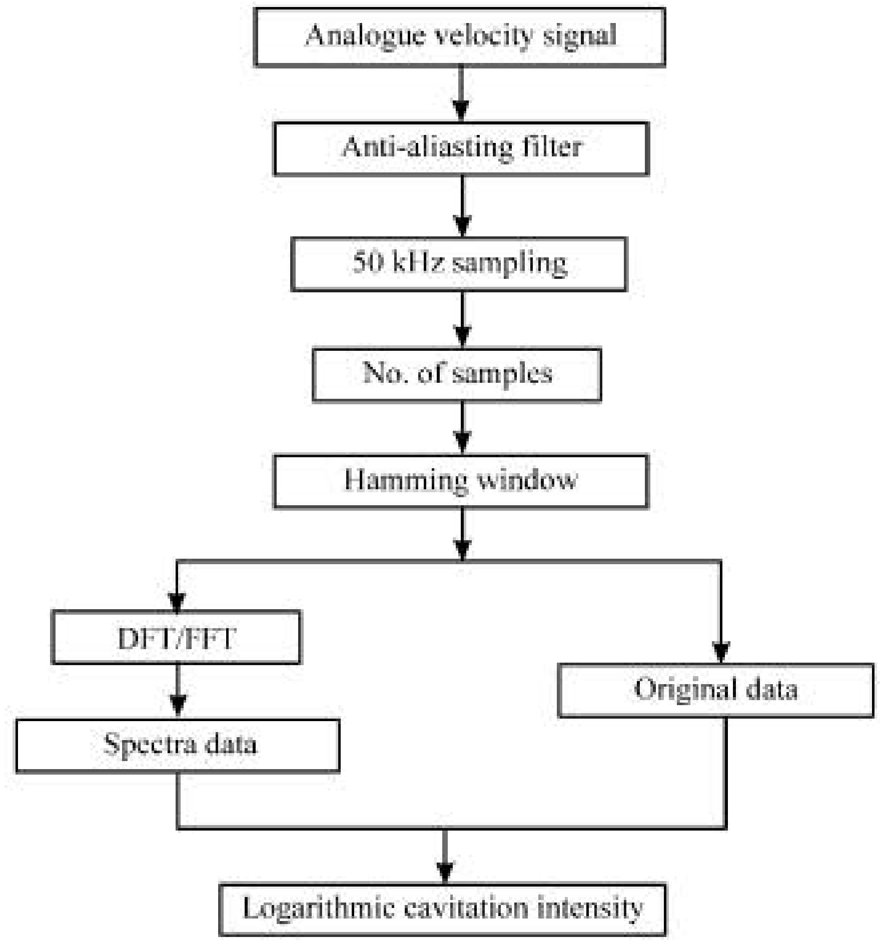

Fig. 9: The study approach to quantify cavitation intensity

where, x (n) is the filtered data and X (k) is the spectra data of the original signal, i.e.,

$$X(k) = \frac{1}{N}\sum_{n=0}^{N-1} w(n) \times x_{\text{original data}}(n) e^{-j(2\pi/N)kn} \quad (5)$$

In Eq. 5, N is the No. of samples used in both cases and w (n) is the Hamming window function. The cavitation intensity was finally defined as the Logarithmic Cavitation Intensity (LCI):

$$\text{LCI} = \ln\text{(average energy)} \quad (6)$$

where, average energy is either from spectra data (Eq. 3) or from filtered data (Eq. 4).

Figure 10 shows the LCI calculated in the time domain, versus cavitation intensity. It is clear from Fig. 10 that occurrence and rising the cavitation intensity leads to increase in LCI. Thus it is possible to introduce LCI as a proper criterion in order to reveal cavitation characteristics. Figure 11 show the cross correlation between the LCI calculated by the average energy in the time domain and the average energy in the frequency domain (using a Hamming window). Figure 11 clearly indicates that using either a filter or a Discrete/Fast Fourier transform technique can achieve the same result in the cavitation detection system. Since, the calculation of LCI in the time domain (using the filtered data) is much simpler to implement than using the spectra data, LCI in the time domain utilized to quantification of the cavitation intensity.

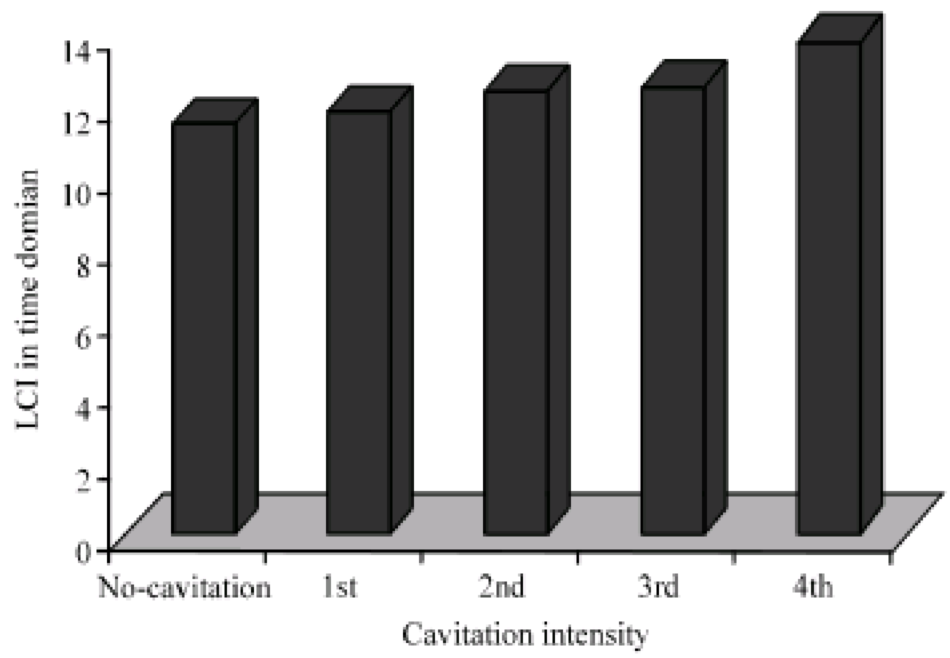

Fig. 10: LCI in time domain, versus cavitation intensity

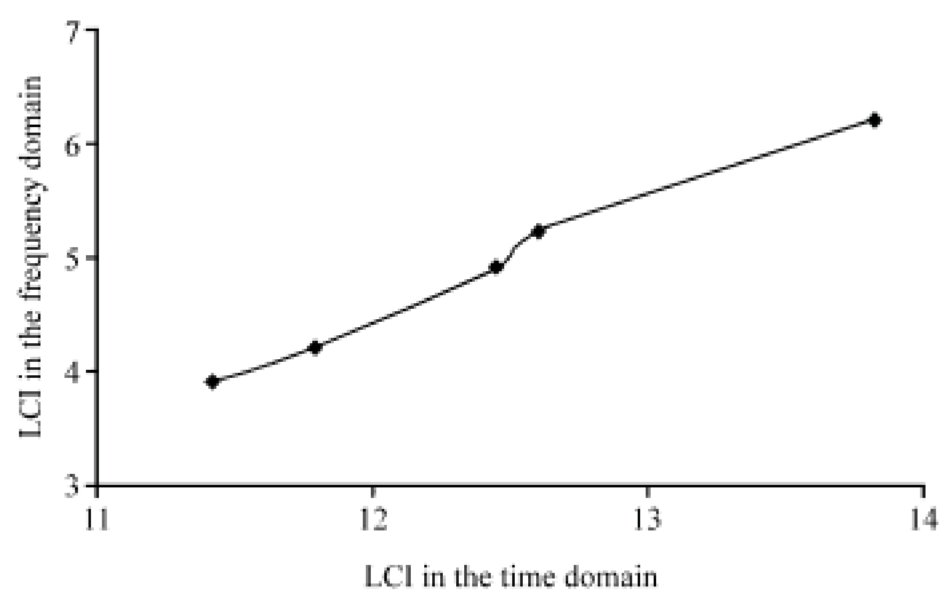

Fig. 11: Cross correlation between the LCI in the time domain and in the frequency domain

CONCLUSIONS

The body oscillation of a pumping set depends on its speed and load and on the instability in the pump. It can also appear due to cavitation. Cavitation as a source of instability causes vibration, noise, pitting and material erosion and deterioration of pump performance.

In this study, cavitation detection and measurement its intensity in an axial flow pump has been systematically studied from the signal processing as well as the instrumentation point of view. A telemetry system comprising a laser velocity probe was successfully installed and used to monitor cavitation erosion induced oscillation. The pump structure oscillation has been analyzed by other researchers too, but the main contribution of this study is introduction of the LCI as an index of cavitation occurrence and its intensity inside the pump. Utilization either a filter or a Discrete/fast fourier transform technique can achieve the same result in the cavitation measurement system. Since the calculation of LCI in the time domain (using the filtered data) is much simpler to implement than using the spectra data, LCI in the time domain utilized to quantification of the cavitation intensity.

Though the 3% drop in pump pressure head has been turned to be a standard method to detect cavitation initiation, monitoring the LCI seems to be a better indicator. In order to use the static pressure to monitor for cavitation, two additional measurements (fluid velocity and fluid temperature) are required. This is because the actual NPSHA is not solely dependent on the static pressure, but is also a function of the average velocity and the vapor pressure of the fluid. In turn, the vapor pressure of the fluid is a function of its temperature. LCI, on the other hand, requires only one measurement. The other advantage of using the LCI index reveals of the fact that whereas monitoring the NPSHA is an indirect indicator of cavitation existence or not in the pump, the LCI is a direct indication of cavitation, not only for its occurrence identification, but also for its intensity measurement.

While the present study is one of the leading in cavitation measurement inside an axial flow pump, its results and the proposed method is completely adjustable to other pumps and hydraulic devices. The results also demonstrate that the proposed method is capable of detecting cavitation by simple hardware with low sampling frequency, leads to reduction the computation time as well as hardware complexity and cost.

REFERENCES

Al-Hashmi, S., F. Gu, Y. Li, A.D. Ball, T. Fen and K. Lui, 2004. Cavitation detection of a centrifugal pump using instantaneous angular speed. Proceeding of 7th Biennial Conference on Engineering Systems Design and Analysis. Manchester, Jul. 19-22, American Society of Mechanical Engineers, pp: 185-190.

Alfayez, L. 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. J. NDT. E. Int., 38: 354-358.

Brujan, E.A.,T. Ikeda and Y. Matsumoto, 2008. On the pressure of cavitation bubbles. Exp. Ther. Fluid Sci., 32: 1188-1191.

Europump, 1999. NPSH for Rotodynamic Pumps: A Reference Guide. 1 Edn., Elsevier Science Ltd., UK., pp: 33-37.

Farkas, I. and Z. Pandula, 2006. Problems with conventional vibration measurements by detection of cavitation operating of centrifugal pumps. Proceeding of 7th International Conference on Vibration Measurements by Laser Techniques. Ancona, Jun. 19-22, Society of Photo-Optical Instrumentation Engineers, pp: 63450Z1-63450Z7.

France, J.P. and J.M. Michel, 2005. Introduction-The Main Features of Cavitating Flows. In:., Fluid Mechanics and its Applications-Fundamentals of Cavitation, Moreau, R. (Ed.). Kluwer Academic, New York., pp: 5-12.

Futakawa, M., H. Kogawa, S. Hasegawa, Y. Ikeda and B. Riemer *et al*., 2008. Cavitation damage prediction for spallation target vessels by assessment of acoustic vibration. J. Nucl. Mater., 377: 182-188.

Gao, X., R. Stone, C. Hudson and I. Bradbury, 1993. The detection and quantification of knock in spark ignition engines. Proceeding of the International Fuels and Lubricants Meeting and Exposition, Oct. 1-15, SAE International, Philadelphia, pp: 932759-932759.

Gulich, J.F., 2008. Suction Capability and Cavitation. In: Centrifugal Pumps. 3rd Edn., Springer- Verlag, Berlin, UK., pp: 298-316.

Guogang, W., G. Ma, D. Sun, H. Yu and H. Meng, 2008. Numerical study on fatigue damage properties of cavitation erosion for rigid metal materials. J. Univ. Sci. Tech., 15: 261-266.

Hattori, S. and M. Kishimoto, 2008. Prediction of cavitation erosion on stainless steel components in centrifugal pumps. J. Wear, 265: 1870-1874.

Hodnett, M. and B. Zeqiri, 2008. Toward a reference ultrasonic cavitation vessel: Part 2: Investigating the spatial variation and acoustic pressure threshold of inertial cavitation in a 25 kHz ultrasound field. IEEE Trans. Ultrason. Ferroelectrics Freq. Contr., 55: 1809-1823.

Karpiouk, A.B., S.R. Aglyamov, F. Bourgeois, A. Ben-Yakar and S.Y. Emelianov, 2008. Quantitative ultrasound method to detect and monitor laser-induced cavitation bubbles. J. Biomed. Opt., 135: 030501-030501.

Lee, H., E. Akagawa, E. Tatsumi and Y. Taenaka, 2008. Characteristics of cavitation intensity in a mechanical heart valve using a pulsatile device: Synchronized analysis between visual images and pressure signals. J. Artif. Organs., 11: 60-66.

Maulik, D., 2005. Doppler Systems: Physical principles of Doppler Ultrasonography: Doppler Ultrasound in Obstetrics and Gynecology. 2nd Edn., Springer, New York, pp: 9-16.

Suslick, K.S. and D.J. Flannigan, 2008. Inside a collapsing bubble: Sonoluminescence and the conditions during cavitation. Int. Rev. Phys. Chem., 59: 659-683.

Tsudaa, S. and S. Takagib, 2008. A study on the growth of cavitation bubble nuclei using large-scale molecular dynamics simulations. Fluid. Dynam. Res., 40: 606-615.

Xu, R., X. Chen, Z. Shen, J. Lu and X. Ni, 2005. Experimental and theoretical study of cavitation-induced mechanical effect on a solid boundary. J. Hydrodyn., 6: 724-729.

Zhang, M., G. Wang and X. Li, 2008a. Design and application of cavitation flow image program. Proceedings of International Symposium on Photoelectronic Detection and Imaging 2007: Image Processing, Beijing, China, Sept. 9-12, The International Society for Optical Engineering, pp: 66230H-66230H6.

Zhang, X.B., L.M. Qiu and Y. Matsumoto, 2008b. Computational fluid dynamic study on cavitation in liquid nitrogen. Cryogenics, 48: 432-438.

Zheng, Y.G., S.Z. Luo and W. Ke, 2008. Cavitation erosion-corrosion behavior of CrMnB stainless overlay and 0Cr13Ni5Mo stainless steel in 0.5M NaCl and 0.5M HCl solutions. J. Tribol. Int., 41: 1181-1189.