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Cavitation Detection on Hydraulic Machines

SUMMARY

This paper gives an engineering review of the phenomenon of cavitation on hydraulic machines: turbines, pumps and ships propellers. The types of cavitation and its consequences are presented by the cabinet study of the results of relevant researches on models and real plants. In the special focus of this paper are the techniques of exploration of cavitation erosion: visual examination, measurements of pressures and vibrations and CFD methods.

KEY WORDS

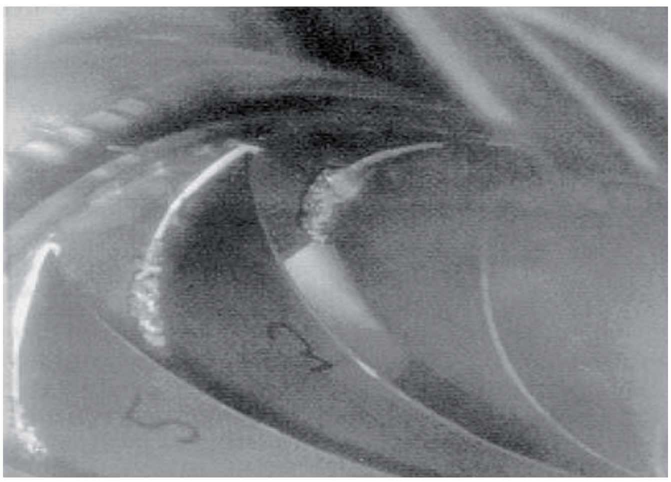
Cavitation, turbine, detection, pressure

1. INTRODUCTION

Liquids usually have characteristic that change chemical phase from liquid phase to vapour phase. Phase changes are introduction in cavitation phenomenon. Cavitation in cosmetic surgery is very positive phenomenon while for hydraulic turbomachinery is negative phenomenon. This is generally an undesirable phenomenon, which cannot be avoided, but scientists, engineers and businessmen can reduce its harmful effects by using various techniques, more or less successfully, by detecting cavitation. It is in focus of interest of this paper.
Cavitation as unwanted process appears at turbomachinery, and especially at water turbines pumps etc. Typical cavitation on hydraulic machines like water turbines and screw propeller are shown at Fig 1: a) Francis turbine – cavitation vortex [1], b) Ship propeller [2], c) Francis turbine - inlet cavitation [3], d) Francis turbine - outlet cavitation [3], f) pump cavitation, [4].

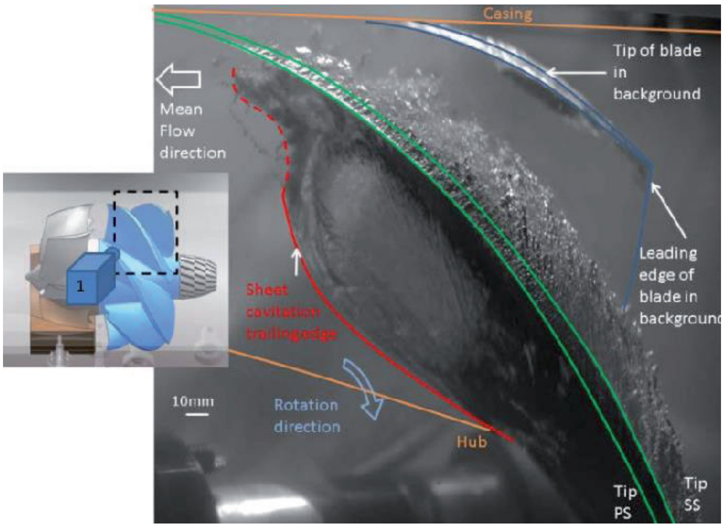
a) [1]

b) [2]



1 c) [3]

d) [3]



f) [4]

Figure 1. Cavitation on hydraulic machines

The occurrence of cavitation depends directly on the hydraulic performance of the machine, the rotor profile and material selection, and the mode of operation of the machine, percentage of dissolved gases, high temperatures and low viscosity, impurities in the form of particles and gas also have an effect on cavitation. [5] Also the geodetic height of machine is also very important.
Cavitation (Ger. *kavitazion*, franc. *cavitation*, lat. *cavitas*, *cavus*: hollow, cored) is cavity, empty space, [6].
Well, let's start with, every engineering methodology is always based on a clear and unambiguous analysis of the occurrence, process, or generally speaking, of an observed problem. Cavitation can be observed in two different ways as vaporous cavitation and as gaseous cavitation. For hydraulic machines vaporous cavitation is more frequent than the gaseous cavitation.
What is cavitation? In hydrodynamics cavitation is a phenomenon in which rapid changes of pressure in a liquid lead to the formation of small vapour-filled cavities, in places where the pressure is relatively low. Cause of cavitation is mechanical. Using the Bernoulli equation the pressure is lower where fluid velocity is higher. If the pressure is lower than the vapour saturation pressure than the cavitation bubbles occurs, [6].
Saturation pressure p_{va} depends on type of liquid and temperature. Water at 100°C saturate at pressure of p_{va} = 101.325 kPa, but at room temperature of 20°C saturate at pressure of p_{va} = 2.337 kPa.
When the cavitation bubble or cavity filled with the vapour phase reaches the area of static pressures higher than the evaporation pressure p_{va} and pressure in the liquid rises, vapour bubble implode (negative explosion), Figure. 2, [3].

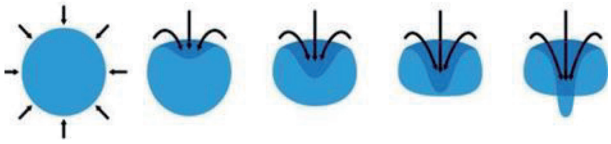


Figure 2. Cavitation process [3]

Collapsing voids that implode near to a metal surface cause cyclic stress through repeated implosion. These results in surface fatigue of the metal causing a type of wear also called "*cavitation*".
Implosion effect is damaged surface and that is called cavitation erosion. Small pores, cracks and holes form on the surface of the wall, which increase over time, not only because of the further mechanical destruction of the material by the implosions of the cavitation bladders, but also by chemical processes that cause accelerated corrosion in the damaged places.
Likewise, these implosions near the wall, in addition to causing erosion of the material, also cause vibrations and noise. Therefore, the influence of cavitation, as a frequent occurrence on the blades of pumps and water turbines, on the wings of a ship's propeller, in hydraulic systems, etc., tends to be reduced. For example, cavitation erosion of ship's propellers is reduced by the use of more resistant materials, by selecting more favourable wing profiles, by installing systems that supply air to the bolt of the bolt, which reduces the rate of implosion, and more, [6].
Cavitation can also be caused by the formation of bubbles that are not filled with liquid vapour, but with gases dissolved in the liquid. Namely, if the pressure in the liquid is higher than the evaporation pressure of p_{va} but lower than the saturation pressure of the gases, gases are generated from the liquid by forming bubbles. When pressure increase again, bubbles disappear without erosion potential because compressibility of gasses dims implosion and hydraulic stroke.
While the vapour cavitation is very rapid, it occurs in micro seconds, gaseous cavitation is slower, and accruement time depends on volume flow.

2. CAVITATION EFFECTS

Cavitation effects, from aspect of the undesirable hydrodynamic process, can divide into mechanical and physical-chemical. This effects can be spotted because of changes of cavitation bubble dimension from first appear than to implosion, Table 1, [6,7].
Table 1. Effects of cavitation [6,7]

Physical - chemical	Mechanical
Pressure and temperature changes)	Cavitation noise
Sonochemical processes	Attenuation of flow caused by forming of vapour bubbles
Sonoluminescence	Strong vibrations
Cavitation corrosion	Material erosion

Cavitation usually has negative effect such as: decrease of efficiency, increase of noise and vibrations, and can cause damage during bubble implosion in front of surfaces. Bubble implosion leads to cavitation erosion. That erosion has unwanted consequences, it is pitting.
It is known that pitting is result of continuous metal surface erosion. The technical standard IEC 60193 prescribes the permissible values of pitting, for example on Francis turbine runners is approx. 40 mm. Average losses on observed blades are 5 kg/m^2 for 10 000 work hours, and repairs have been done every 40 000 working hours, [8].
Relevant international standards does not describe permissible amounts of eroded material depending to runner dimensions, for example; blade thickness. Figure 3. Show examples of damage at Francis turbine runner: a) at hub b) surface cavitation at blades, c) cavitation of inlet edge, [9].

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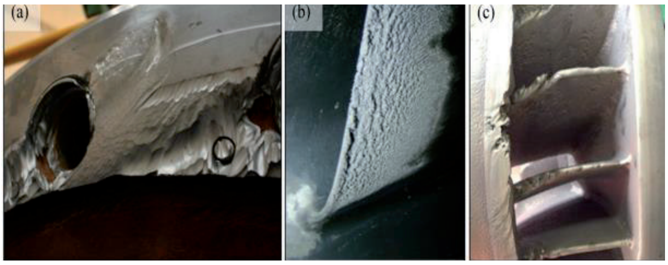

Figure 3. Cavitation erosion damage at Francis turbine[9]

Fig. 4: a) and b) is given example of pump cavitation erosion, and at c) is given example of screw propeller ruined by cavitation erosion, [10] and [11].

Figure 4. Cavitation erosion damage at pump and ships propeller [10, 11]

Erosion damages propagate during the machine operation and can lead to crack occurrence. Timely rehabilitation is necessary. However, if the reconstruction causes a change in the geometry of the blade, such a location can become a source of new separation of fluid flow, i.e. cavitation flow and new erosion. Increased vibration, noise and reduced usability of such a machine must not be neglected. The rate of destruction of solid wall material under the influence of the cavitation process is not always the same and depends on several factors from which they can be separated into:

frequency – higher frequency means faster destruction of materials;

material characteristic;

cavitation bubble dimension – the damage also depends on the size of the bubbles, smaller bubbles have a higher frequency of implosion and often cause more damage than larger bubbles but have a smaller effect on the rest of the system;

hydraulic machine operation condition – cavitation increases frequently when operating modes change, or sudden changes in the system occur.

Electric Power Research Institute, EPRI [12] separate most important causes of cavitation erosion such as: geodetic position of machine, hydraulic turbine design, runner blades profile, machine operation mode, water quality, material etc.

Cavitation cannot be avoided but its effects can be minimized. During the exploitation it is important to take care about EPRI important causes, such as machine operation mode.

3. CAVITATION TYPES

There is a whole series of categorizations of the phenomenon of cavitation, the most common criterion being the location of occurrence, Table 2. The whole series of studies in the focus of research activity has just mentioned criterion.

For example, Franc & Michel specify eight types of cavitation, Franc[13] two types while Ozonek [14] mention four types of cavitation, and Avelan [15],[16] mention eight types of cavitation.

Authors take place of origin as division such as: inlet edge cavitation, surface cavitation, detached vortex cavitation, hub cavitation, interblade vortex cavitation, draft tube swirl, Von Karman vortex cavitation etc.

Basic criterion for categorization of cavitation is the type of hydraulic machine on which it occurs: pumps, turbines, marine propellers. Physically, two basic types of cavitation can be determined: vortex cavitation, and bubble cavitation, and their combination, and if the criterion is location in the broad sense, then profile cavitation, gap cavitation and central cavitation are distinguished Profile cavitation will occur when a fluid obstructs a surface at a certain angle, provided that the pressure on one side of the profile is higher and on the other is less than the ambient pressure. Vapour bubbles appear on the profile surface when the pressure drops below the evaporation pressure of the water on the pressure side. The bubbles persist until the pressure is higher than the evaporation pressure, followed by condensation and cavitation erosion. According to the intensity of cavitation, profile cavitation can be defined as: initial stage, advanced stage, super cavitation, Šarc at al.[17].

The cavitation in the clearance is due to the excessive clearance between the rotor and the turbine housing. Previously, the phenomenon of pressure and suction side has been clarified, and if the gap between the impeller blade and the turbine housing is too large, the fluid overflows from the pressure side to the suction side, [5].

Central cavitation generally occurs when the turbine is operating in optimum area.

Table 2. Types of Cavitation - Research Results

Researchers	**Types of cavitation-Research Results**
Franc &Michel [13]	Travelling bubble cavitation, bubble cavitation in the shear layer, localized bubble cavitation, localized attached cavitation hub vortex cavitation, tip vortex cavitation, detached vortex cavitation, surface cavitation.
Bagienski [18]	Surface cavitation, detached vortex cavitation.
Ozonek [14]	Vaporous cavitation, gaseous cavitation, flow cavitation, vibratory cavitation, acoustic cavitation.
Thakkar at al. [19], Escaler at al. [3]	Flow cavitation, traveling bubbles, attach cavities, vortex cavitation.
Li [20]	Leading edge cavitation, flow cavitation, traveling bubbles, ˊdraft tube swirl; inter –blade vortex cavitation; Von Karman vortex cavitation.
Avelan [15],[16]	Flow cavitation, traveling bubbles, leading edge cavitation, inlet edge cavitation, inter –blade vortex cavitation, Von Karman vortex cavitation, cavitation whir, hub cavitation.

4. CAVITATION DETECTION TECHIQUES

4.1 General approach

Cavitation detection techniques or methods are numerous and can be categorized according to different criteria, as well as types of cavitation. Thus different authors have different approaches depending on the interest and experience of the researcher. However, it should be noted that cavitation is a phenomenon or characteristic of hydraulic machines that, unfortunately, cannot be transferred with certainty from a model to a prototype of a real plant. It has just been mentioned very important in the development of cavitation detection diagnostics.

If technical and technological conditions are taken as a categorization criterion, then two basic categories can be distinguished: cavitation detection: first, cavitation detection on the model i.e. in laboratory conditions, second, cavitation detection on the prototype i.e. in real plant conditions. Furthermore, if the physical characteristic of the measurement is taken as a categorization criterion, then five basic types of cavitation detection and five methodological groupings are naturally determined: visual methods, acoustic methods, pressure measurements, vibrational methods and ultrasonic method. There is also the division of cavitation detection methods into: direct and indirect methods. The direct method is just visualization while all other methods are indirect. Methods for detecting cavitation in real plants are based on measurements and analysis of received signals, which is not an easy task since, depending on the shape of the turbine and operating conditions, cavitation always occurs in other places and in other forms. Furthermore, the measured signals on the sensors can be interfered with by noise coming from a part of the plant other than the one we primarily measure. Therefore, it is necessary to carefully locate a good placement of the measuring sensor. For vibration measurement, it is best to

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choose accommodation on the turbine bearing, while pressure is best measured on whole or spiral housings. It is quite important that the measurements and signals obtained are well studied and processed on the basis of a large enough sample to be as accurate as possible. It has already been emphasized in previous sections that cavitation is an unstable phenomenon that raises low-frequency oscillations of pressure as well as pulses of high-frequency pressure. This pressure oscillation depends on the dynamics of the cavities, e.g. shape, type, location, and the pressure pulse occurs due to the implosion of these cavities. Both phenomena emit vibrations and acoustic noise and are propagated by hydrodynamic and mechanical systems. Thus, using suitable sensors that measure vibration and cavitation noise, the phenomena of cavitation in a hydraulic machine can be detected or analysed. Sensors such as accelerometers, acoustic emission sensors are attached to the outer walls of fixed components, and dynamic pressure transducers are mounted on the wet wall, Khakurel [5].

4.2 Literature Review

Several cavitation detection methods have been investigated. Table 3 gives a brief overview of the results of relevant studies of the cavitation phenomenon on hydraulic machines, with particular emphasis on cavitation detection techniques.

Table 3. Research results –cavitation detection

Researcher	Techniques for cavitation detection
Thakkar [19]	Pressure measurement, visual methods, vibration measurements
Koivoula et al. [21]	Visual methods, noise measurements, Pressure measurement and vibration measurements, ultrasonic methods
Šiško [6]	Pressure measurement, acoustic method, vibration measurements,
Li [20]	Pressure measurement, visualising, vibration measurements,
Escaler et al. [22]	Pressure measurement, visual methods, vibration measurements
Cecio et al. [23]	acoustic method
Eich [24]	Pressure measurement, acoustic method
Backe et al. [25]	Pressure measurement, vibration measurements

Pressure, vibration and acoustic pressure measurement are relatively effective methods of cavitation detection.
Grätz et al. [26] and Riedel et al. [27] studied steady-state flow properties in cavitation openings. They obtained parameters that can relatively reliably estimate the occurrence of cavitation in openings.
Wiklund et al. [28] and Myllykylä et al. [29] studied the pumping ability of different pumps. They recorded remarkable results - a decrease in pump output when the suction portion of the pump is cavitated.
Bajić [30] and Eich [24] studied the cavitation noise in the cavitation orifice flow and analysed the recorded acoustic pressure with visual inspection. He concluded that the acoustic method detected the onset of cavitation prior to the visual method. Eich found that at the onset of cavitation, the first responses were in acoustic pressure at high frequencies (> 20 kHz).
Backè et al. [25] used accelerometers in their research. They found that the accelerometer signal indicates cavitation before changing the flow properties at steady state.
Visual inspection in the cavitation orifice stream has been used in several studies (e.g., Šiško [6], Eich [24]). Bajić [30]), In these studies, relatively slow cameras were used; High-speed photography has been used in cavitation research in water tunnels (e.g., Knapp et al. [31]). Slow cameras detect the presence of cavitation, but only a quick photo gives detailed details and information about the size and speed of cavitation cavities.
Koivula et al. [21] have explored a number of useful results by exploring cavitation detection techniques, and a brief summary of the above is given below
Direct cavitation detection is only possible if measuring or detection instruments can access the cavitation zone. This is a very difficult task due to the fact that cavitation as a phenomenon is usually very local in nature. Cavitation detection can only be done directly by checking the existence of cavitation bubbles. Visualization of bubbles in flow passages can be successfully done if light can be scattered in the observation zone. This requires at least two windows for visualization. Observing the behaviour of ultrasonic waves can reveal the existence of cavities. High flow speed causes ultrasonic waves to deflect. Due to the difficulty in direct detection methods, several indirect cavitation detection methods may be considered. In indirect or indirect methods, measurements are focused on the shock waves generated by the cavitation bubble implosions. Impact waves propagate relatively quickly and far and the position of the sensor is not as limited as in direct measurement. In the observed study, cavitation was indirectly detected by pressure sensors, accelerometers and acoustic instruments. The results showed that the initial phase of cavitation was characterized by intense high frequency pulsations. When cavitation develops, the pulse also extends to lower frequencies.

4.3 Pressure measurement

Pressure measurement is a standard technique for the determination of cavitation on hydraulic machines and is most commonly used in combination with vibration measurement to achieve the most accurate results of the cavitation process. When a bubble enters a high-pressure zone, it vibrates and induces vibrations as well as pressure pulses, Ceccio & Brennen [32].
Escaleret et al. [33] implemented cavitation detection experiments on a Francis turbine by measuring pressure with demodulation amplitude. Figure 5 shows the frequency pulse pressure for the cavitation bubble type and the bez (flow) flow without cavitation. As can be seen, whenever pressure waves are generated due to cavitation, high peaks in the frequency band are obtained.

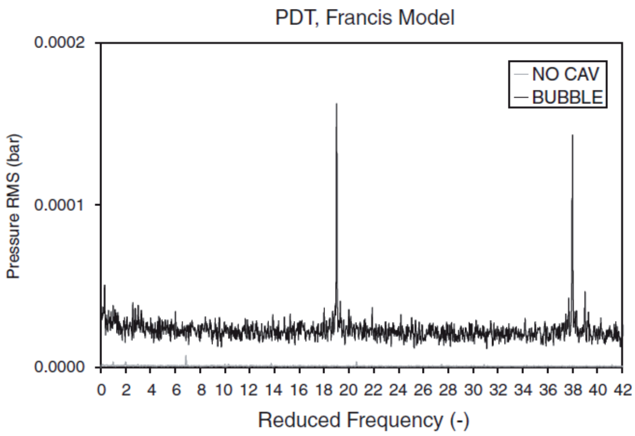

Figure 5. Peak pressure values measured [33]

Pressure changes at draft tube are presented at Figure 6, for different machine operational conditions, and is obvious that the cavitation detects in lower frequency range than in case Peaks are presented when cavitation occur.

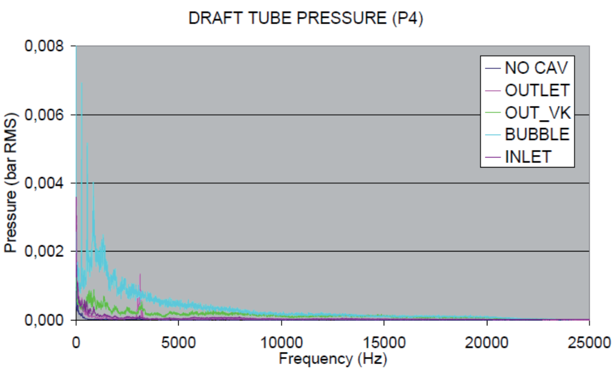

Figure 6. Draft tube pressure at different condition [33]

In their extensive experimental studies, Koivula et al. [21] used, among other things, the pressure measurement method, and they came to a number of conclusions. For example, in indirect cavitation detection methods, the question of the measurement of shock waves caused by cavitation bubble implosions is usually raised. Bubble inhibition is first seen at very high frequencies and therefore very fast pressure transducers are required. The propagation of shock waves continues from the fluid to the environment.

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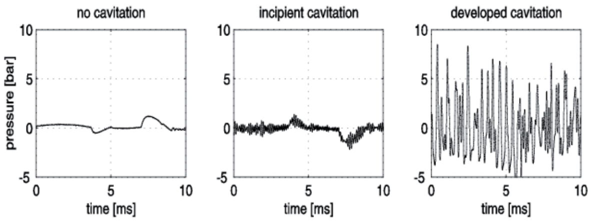

Figure 7. Draft tube pressure for different cavitation periods [10]

The observed study used high - speed transducers to measure peak-to-peak vibration pressure. Figure 7 shows diagrams of time dependence of pressure and the appearance of cavitation rising from left to right.

4.4 Visual method

This method is very popular in last decade especially at hydraulic machines model tests, Šiško [6], Bajić [30]. It is based on the use of stroboscopes and superfast cameras that hang against the Plexiglas window, and sometimes whole sectio
ns of the test station are made of plexiglas, for example, Figure 8.

Figure 8. The test station of the propeller [10]

The test station of the Francis turbine model is shown in Figure 9. In an extensive study of the cavitation phenomenon conducted by Illiescu et al. [1] used LDV (Laser Doppler Velocimetry) systems, optical mirror systems, superfast cameras, diffuser pressure sensors.

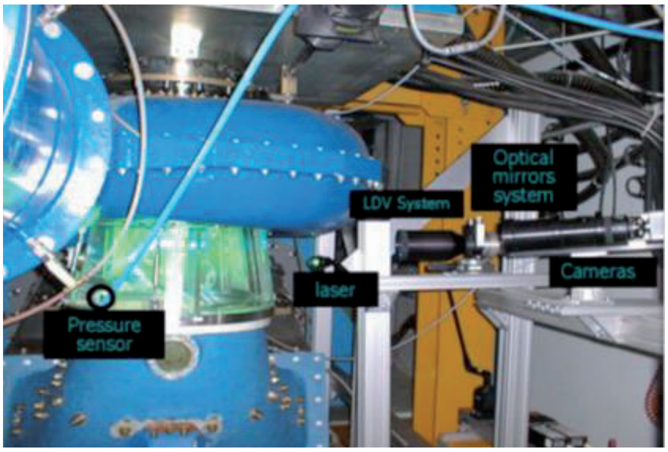

Figure 9. The test station of the Francis turbine model [1]

Avelan [15, 16] investigated cavitation using centrifugal pumps and Francis turbines by visual method.
The results of his research show that the occurrence of cavitation on centrifugal pumps is primar-.ily a function of the flow coefficient ϕ, which depends on the value of the relative velocity and the angle of incidence of the liquid at the inlet edge of the blade. In principle, travelling bubble cavitation occurs on the suction side of the blade while the pressure value is lowest in the rotor throat. At low pump flow rates, the cavitation of the blade inlet edge appears, Figure 10. [15]. Also, at low values of the cavitation number ˙σ, a cavitation swirl appears at the inlet of the pump rotor [16].

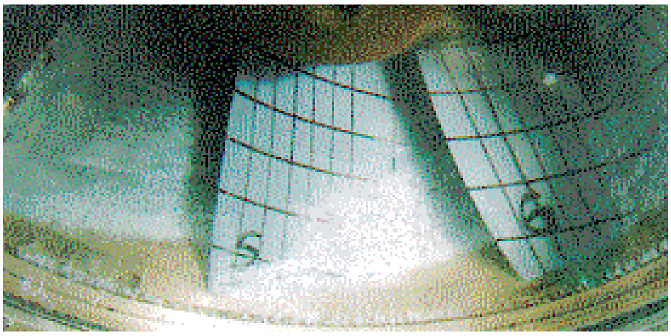

Figure 10. Leading edge cavitation at inlet of pump [15]

Cavitation vortex at Francis turbine draft tube is visualized through the Plexiglas, Figure 10.
A more modern approach to the visualization method is taken by well-known Slovenian researchers Širok et al. [34] who quantified the occurrence of cavitation on Kaplan turbines by the method of computer aided visualization, Figure [11]. Using CCD (Charge-Coupled Device) cameras, stroboscopes and computers (video graphics card) in different turbine operating modes, the occurrence, shape and intensity of the cavitation vortex in the throat of a Kaplan turbine diffuser were analysed.

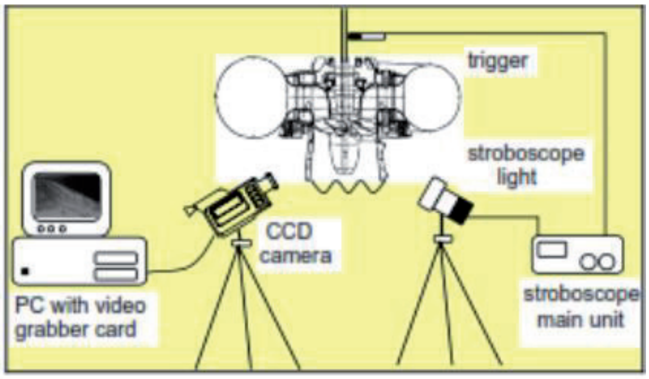

Figure 11. Computer aided visualization [35]

Patel [36] carried out a very interesting study of the occurrence of cavitation at a pump operating in turbine mode. A glass tube was installed at the inlet of the diffuser to visualize the cavitation process, Figure 12.

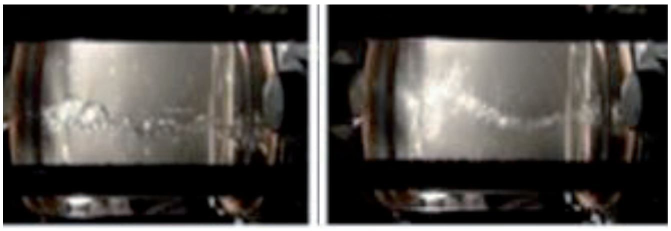

Figure 12. Travelling bubble type cavitation (left) Vortex rope cavitation (right) `[36]

Two types of cavitation are mainly observed: bubble traveling cavitation and cavitation vortex.

4.5 Vibration measurement

Methods for detecting cavitation on real machines are, in principle, based on measurements and analysis of induced signals. Detection of cavitation is not an easy job at all, because it is in the function of several variables, such as the design and operating state of the machine, the type of cavitation, its location and behaviour.
Cavitation vortices and unstable cavities with large oscillating volume cause interference with the main stream and lead to strong pressure pulses within the hydraulic system. This low frequency fluctuation can be detected by means of pressure transducers mounted on the diffuser wall. If the fluctuation intensity is strong, detection can also be performed with structural vibrations. Thus, in this case, the procedure only requires an analysis of the frequency content of the pressure and

vibration signals in the low frequency range, Bajić [30].
Furthermore, the measured signals can be contaminated by noise from another source whose sources can be quite diverse, i.e. of hydrodynamic, mechanical or electromagnetic origin. Therefore, selecting the most appropriate sensors and measuring position on the machine are fundamental to improving the quality of cavitation detection.
Most of the researchers who deal with these issues agree with this. A number of successful studies have been implemented, for example Escaleret et al. [22, 33] conducted experiments and vibration analysis and proposed to measure the structure of cavitation noise transmitted by liquid. The amplitude of a particular frequency range can be compared for different operating conditions by calculating the intensity of the time signal spectrum. The vibration peaks with amplitude demodulation are shown in Figure 13. High frequency analysis cannot give definitive results as other phenomena can also cause machine vibration and thus perform high frequency amplitude demodulation.

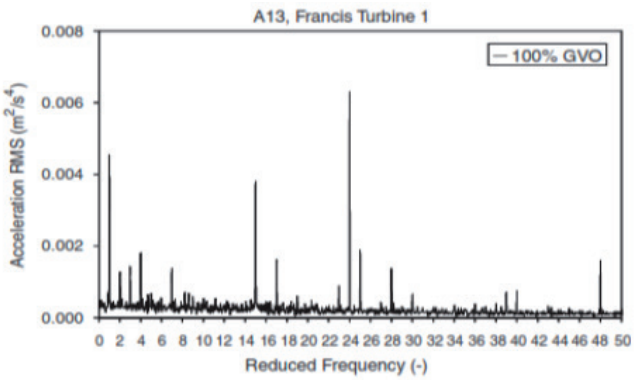

Figure 13. Vibrations peak with amplitude demodulation, [22]

In the observed research, experiments were performed on the Francis turbine model; vibrations were measured using three accelerometers in different positions. One on the shaft and two on the 90 degree bearings. Different acceleration values within the given frequency range were measured for different openings of the control blades and it was concluded that the turbine was separated from its BEP (Beam Experimental Platform), higher peaks were obtained at the frequency of 6 kHz as shown in Fig. 14 and Fig.15. where the Guide Vane Opening [%] is the opening of guide vane mechanism.

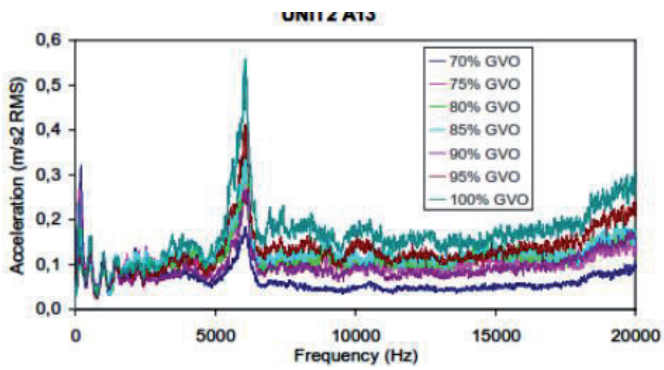

Figure 14. Vibration at bearing for different GVO,[22]

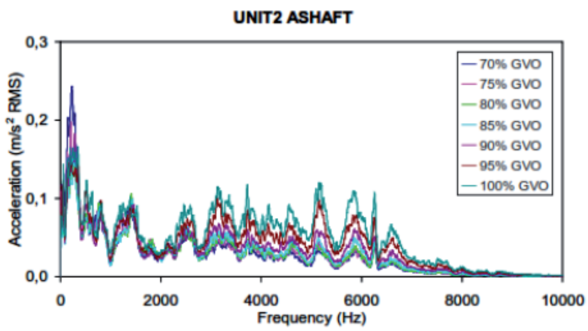

Figure 15. Vibration at shaft for different GVO,[22]

Koivula et al. [21] also explored the method of detecting cavitation by measuring vibrations.

4.5 Cavitation noise measurement

Studying vibrations, acoustic emissions, and dynamic pressure levels in a high frequency range is a well-known technique for detecting cavitation. The amplitudes of the set frequencies can be compared for different operating conditions by computing the time signal spectrum. A steady and sharp increase in frequencies when compared to a state where there is no cavitation can indicate the presence of cavitation. The use of acoustic emission sensors allows this analysis to be extended to upper frequencies that accelerometers cannot reach. The information we get is sometimes irrelevant because sometimes we get signals and frequencies from other parts of the system or environment. Therefore, it is necessary to use an amplitude demodulation technique to improve diagnostics.
Eskaler et al. [22, 3] performed experiments on a Francis turbine model by measuring acoustic emission. The figure shows the measured acoustic emissions for the different openings of the control blades (A0) for the frequency range from 0 kHz to 20 kHz. The values increased with increasing GVO GVO with the exception of the abrupt fall of 90% measured by the accelerometers. Bajić [30] performed measurement on Kaplan turbine, Dubrava HPP – Croatia.
Patel et al [37] performed acoustic emission analysis on a pump as a PAT (Process Analytical Technology) turbine operating at different speeds to detect cavitation.
Koinvoul et al. [21] also used an acoustic method in their extensive cavitation studies. A number of conclusions have been reached, for example: more extensive information on cavitation occurrence is obtained when measuring cavitation noise with a large range of high frequencies. Moreover, if the results are plotted as a frequency spectrum, the onset and development of cavities is clearly seen. The measured frequency spectrum of the acoustic pressure is shown as a 3D graph in Figure 16. Over a period of 3s, one can clearly see the moment of cavitation occurrence in a sharp increase in acoustic pressure at high frequencies (> 8 kHz). When cavitation develops, the acoustic pressure also extends to lower frequencies. The same trend is observed in spectral analysis when measuring the pressure and vibration of the origin and development of the cavitation process.

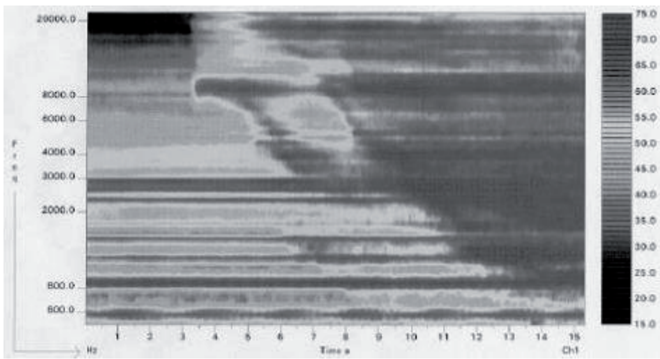

Figure 16. Frequency spectrum of acoustic pressure [21]

Ceccio et al. [23] and [32] showed that cavitation noise analysis is a useful tool for investigating the properties of cavitation phenomena. It is easy to measure the noise structure in a turbine, while it is very difficult to measure noise transmitted to the fluid because it is impossible to fit a pressure sensor in the turbine rotor. It must also be borne in mind that cavitation noise cannot be directly measured, since the signal strength as they propagate is attenuated. Nevertheless, the spectral content of high frequencies and modulating frequencies can be used to detect cavitation.

4.6 CFD Analyses

CFD (*Computational Fluid Dynamics*) is branch of fluid mechanics which uses numerical analyses and solving *Navier-Stokes* equations for predicting and solving problems in fluid mechanics. Computers are used to calculate fluid flow and interaction between liquid and vapour phase with boundary conditions.
In last time CFD is used often for solving most complex problems in turbomachinery worldwide. Supercomputer with powerful processor and better overall performances are needed for better results. And that

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is the problem because the supercomputer cost too much. For cavitation problems CFD can predict fields where cavitation will appear but cannot predict the effectiveness of cavitation erosion.

Two are mean principles in numerical solving of cavitation problems in CFD: first is *mixture model* and the second one is *eulaerian model*. There are lot numerical models implemented in these two mean principles such as: 1) *Singhal* i sur. – better known like *Full Cavitation Model*, 2) *Zwart-Gerber-Belamri*, 3) *Schnerr* & *Sauer*, and like *Kunz*-a...

The most common models for cavitation modelling are IFM (*Intensity Function Method*), GLM (*Gray Level Method*), DBM (*Discrete Bubble Method*). There is a combination of GLM i DBM method and that is EPM (*Erosive Power Method*).

Numerous investigators for the first phase investigations use this method. Sedlar et al. [38] described new model for cavitation erosion prediction using numerical modelling of turbulent cavitation. They analysed dynamic behaviour of cavitation bubbles which occur with gradient of pressure change in hydraulic machine. Potential cavitation erosion model is based on energy dissipated by bubble. Energy which has dissipated through bubbles collapse is used for shock wave modelling which spreads from bubble. Part of shock wave energy transmitting to surface represent erosion potential.

Nohmi et al. [39] are using CFD analysed cavitation processes for centrifugal pumps. They used two models: two-stage model for compressible fluids, better known as TE model, and other CEV (*Constant Enthalpy Vaporization*) model. Both models have same results of prediction, Figure 17.

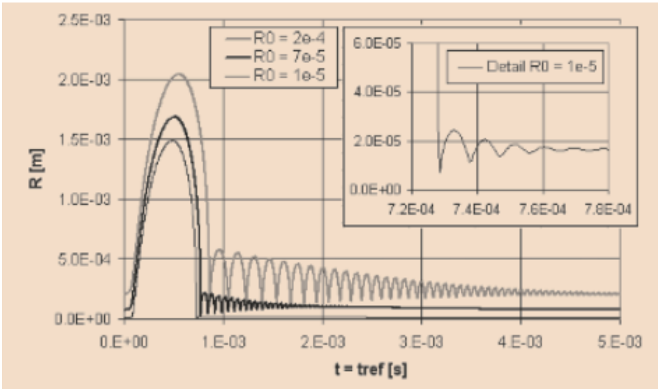

Figure 17. Bubble collapsing [39]

Both models show suction head drop when cavitation occurs. Analyses have shown that for higher fluid velocities model need to be modified. Iosif et al. [40] presented an explicit numerical one model based on finite element method and dual reciprocal method. They suggested using a model to transform 3D flow into 2D problems for an ideal noncompressible fluid. They solved the axisymmetric potential flow using FEM (*Finite Element Modelling*) by determining the distribution of pressure and velocity along the stream. The results were analysed for a reversible hydraulic machine and showed different flow values previously used to determine the cavitation characteristic and the sensitivity curve.

5. CONCLUSION

Cavitation is the undesirable phenomenon at hydraulic machines that can be predicted and with various techniques reduced but never entirely avoided.

Many researchers used various techniques such as visual method, pressure and cavitation noise measurements, CFD methods for predicting and analyses of cavitation. Also techniques are used for prediction cavitation erosion potential.

It is rare to use only one technique. Usually two, three or four techniques are used for reliably prediction.

For model test visual method is most dominant method, but for hydraulic machines in operation pressure and vibration measurement are most used techniques.

Several researchers noticed that the cavitation can be registered firstly with pressure measurement method than with visual method.

It is widely known that the cavitation characteristic can't be translated from model test to real machines. That means it is necessary to invest more time to determine the cavitation characteristic.

Numerical CFD simulations can reliably determine cavitation but cannot predict cavitation erosion with great accuracy. In future the CFD simulations in turbomachinery will be in progress and potentially dominant in determination of cavitation characteristic.

Each of the methods for cavitation detection on hydraulic machines has advantages and disadvantages and there are gaps for improvement. However, the main problem is fact that there are no exactly formula for linking relation from laboratory cavitation test to prototype cavitation, until now. Moreover, real cavitation characteristics can only be obtained on hydraulic machines in operation in the real facilities. Following this, the acoustic method is easy to apply and has significant potential in linking laboratory tests and tests on prototypes. So, future research should put focus on acoustic method and closer cooperation between scientists and engineers involved in the maintenance of hydraulic machines.

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