VISUALIZATION MONITORING OF CAVITATION IN WATER TURBINES

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Abstract: Present methods for cavitation detection in water turbines are based on observation of pressure pulsations, acoustic emission and mechanical vibrations on the turbine casing. In the following a new method of cavitation monitoring, which offers real time evaluation of the cavitation topological structures in the turbine flow field, will be presented. In the paper the application of the method on a model of a Kaplan turbine is presented along with the installation of mechanical equipment on a new power station Doblar II on river Soča (Slovenia).

1. Introduction

Cavitation is usually closely connected with either generation of individual bubbles or connected topological structures of gas phases in liquid, which originally was the homogeneous single-phase structure. Formation of gas structure is the consequence of decrease of absolute pressure to vaporisation pressure at approximately constant temperature. Formatted cavitation bubbles are carried away by the liquid flow. At transition of two-phase flow liquid-gas to pressure range higher than the vaporisation pressure, the steam phase is condensed, and as consequence extreme high frequency and amplitude local pressure pulsation occur [1]. They cause the surface erosion of the flow tract, noise, mechanical vibrations, and modification of flow field of the hydraulic machine.

In hydraulic machines like Kaplan turbine the cavitation occurs in the regions where the velocity gradient is most significant, i.e. on surfaces of elements with large geometrical gradients: rounding, cornered structures, etc. Frequently it occurs on the top of rotor blades, as leading edge and sheet cavitation and vortex type of cavitation on the tip of the blades, where flow separated at blade structures forms low local velocity zones. Between this region and the region of fully-developed flow there occur distinctive shear region zones with high intensive vortex flow. There at low pressure appear the cavitation zones.

The goal of turbine manufacturers is producing machines with minimal level of cavitation in the nominal operating region. At the operation of turbine machines the knowledge of cavitation structure and its sink in the flow field is of the greatest importance. According to the fact that cavitation is connected with efficiency change, increase of noise level and increase of vibrations, the numerous researches are focused on various experimental methods which indirectly via the above mentioned effects estimate the cavitation phenomena in water turbines [2], [3]. Characteristically for all mentioned methods is “indirect” observation of cavitation via
secondary effects, which, however do not contain direct information about space structure of cavitation.
In contrast to the above mentioned methods the aim of this paper is to present the direct method of observation of cavitation topological structure on rotor blades of Kaplan turbine model with aid of computer-aided visualization. Presented method is based on direct observation of cavitation structure in space and time. Cavitation in the presented study is observed visually, without indirect effects like vibration and acoustic power. Various cavitation structures are observed in dependence on integral hydro-dynamical machine parameters. In accordance with IEC [4] regulations the space distribution of cavitation regions is presented along with local dynamic of topological structures in dependence on dimension-less cavitation number $\sigma$ at constant flow number $\phi$, and pressure number $\psi$ of Kaplan turbine model.

Application of visual cavitation monitoring in water turbines depends on various parameters and limitation-conditions. In contrast to model researches, real conditions are worse for cavitation observation on turbine rotor and above all dependent on the size of machine, transparency of water and constructional abilities for installation of equipment into flow tract of the machine. In the paper in continuation first steps of equipment installation on Kaplan turbine of Doblar II power plant are presented. Problems and solutions of illumination, positioning of camera and synchronization of digital image capturing are presented.

2. Integral hydro-dynamical characteristics of KAPLAN turbine model

Integral operational conditions of optional water-turbine are defined with two dimension-less parameters: pressure number $\psi$, and flow number $\phi$, defined as:

$$\psi = \frac{2E}{\pi^2 n^2 D^2},$$

$$\phi = \frac{4Q}{\pi^2 n D^2},$$

Here, the specific energy $E$ (J/kg) is defined as the difference of total energy at turbine inlet and outlet, $Q$ (m$^3$/s) represents the water flow through turbine, $n$ (1/s) rotational speed, and $D$ (m) the outer diameter of turbine rotor. Cavitation number $\sigma$ is a dimension-less quantity, expressing the relationship between absolute pressure $p_s$ (Pa) at turbine rotor, vaporisation liquid pressure $p_u$ (Pa) and specific energy $E$ in the observed operational point.

$$\sigma = \frac{p_s - p_u}{E \rho}.$$  \hspace{1cm} (3)

In compliance with IEC [4] regulations the integral cavitation turbine characteristics is given by functional dependence of hydro-dynamical turbine efficiency $\eta$ from cavitation number $\sigma$, as presented in the Fig. 1.
There the hydro-dynamical turbine efficiency is determined with aid of measured power $P_g$ (W) on turbine shaft and measured hydro-dynamical parameters $E$ and $Q$ (m$^3$/s):

$$\eta = \frac{P_g}{\rho EQ}$$  \hspace{1cm} (4)

All measured operational points are located on the experimental cavitational curve $\eta$ in Fig. 1. In the respective points a to f cavitational structures were investigated. The intensity of expected cavitation is increasing when the cavitational number $\sigma$ at constant hydro-dynamical parameters $\phi$ and $\psi$ is decreased. In the present experiment this was achieved by decrease of the absolute static pressure $p_s$ in the turbine flow field.

3. Experiment

![Fig. 2: The experimental set-up, illumination, and visualization of the cavitation structure.](image)
The experiment was performed on the model of Kaplan turbine. The experimental set-up is presented in Fig. 2. The integral cavitation characteristics of the model are presented in Fig. 1. In the measured operational points (a to f) with aid of computer-aided visualization equipment image sequences of time fluctuation of cavitation structure on selected turbine rotor blade were recorded and digitised. For each operation point a separate image sequence was recorded. The illumination was performed, because the cavitation was investigated on one single blade at selected rotor position, with aid of stroboscope light, triggered by a blade position sensor. Consecutive images were captured by a CCD camera with the sampling frequency 25 f/s. The images from the camera were digitised by 8-bit video frame grabber with a resolution 768x576 pixels. The spatial resolution of a pixel is about 0.2 mm in the present experiment. The length of each time series was 582 images.

The level of grey intensity in space and time forms scalar patterns which can be observed using computer-aided visualization. By successive digitisation of grey intensity distribution shots in restricted areas, simultaneous time series. Method is based on a presumption that cavitation intensity, i.e. portion of a gas phase in the observed space is proportional to the grey level and that the region of cavitation structures collapse is proportional to the region of intensity of grey level fluctuation [5, 6, 8]. From the digitised pictures simultaneous time series, describing the dynamics of the observed patterns is derived, as described below. For this purpose, we selected a limited area 80x56 mm of observation of the flow structure in the centre of the plane of the experimental field. This area was then divided up into 400 windows, each having 20x14 pixels as shown in Fig. 3.

For the assessment of the quantitative behaviour of patterns of the cavitated vortex core, an integer-type scalar’s variable $A(k,t)$ was introduced [5]:

$$A(k,t) = \sum_{l=1}^{14} \sum_{m=1}^{20} E(l,m) \quad E(l,m) = \{0,1,...400\}$$

$A(k,t)$ is proportional to the average light intensity in selected window $k$ at the time $t$. $t$ is the time when the image was captured and $m$ total number of windows. $A(k,t)$ was calculated for each of the operational points a to f.

![Fig. 3: Selection of the observation area. The images are processed with aid of the computer program Dynascan [4,5].](image-url)
4. Results and discussion

Typical time series $A(k,t)$ for operational point $d$ and window $k=55$ is presented in Fig. 4. The examples of cavitational structures on the rotor blade of the Kaplan turbine model in dependence of integral parameters are shown in Fig. 6a. The transition from the operational region without cavitation (regime a) to the region with fully-developed cavitational flow (regime f) can be easily recognised.

![Fig. 4: Time series $A(k,t)$ for the window $k=55$ and operational point $d$.](image)

Here one important feature can be recognised, i.e. the cavitation starts to form on the draft side of the inlet blade edge and gradually spreads up along the outer blade edge towards the outlet edge. At the end it transforms at low values of $\sigma$ in the surface cavitation along the entire blade (regime f). From the integral characteristics in Fig. 1 and continuous transition between the respective structures appertained cavitational structures (from a to f) one can notice that when modifying the cavitational number $\sigma$, the intensity and location of cavitational structure alters.

Quantified cavitational intensity values on the draft side of rotor blade are given in the diagrams of the space distribution of time-averaged scalar function $\overline{A}(k)$ and respective standard deviation $s(k)$:

\[
\overline{A}(k) = \frac{1}{N} \sum_{i=1}^{N} A(k,i) \tag{6}
\]

\[
s(k) = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (\overline{A}(k) - A(k,i))^2} \tag{7}
\]

Here $i = i \cdot \Delta t$, $\Delta t$ being time difference between two consecutive images. $N$ is total length of each time series. From the presented diagrams one can notice that the intensity of the scalar function $\overline{A}(k)$ Fig. 6b and respective standard deviation $s(k)$ Fig. 6c alters with cavitational number $\sigma$. Location and intensity of both variables change in accordance with cavitational structures in the selected areas of observation.

With time-averaging of variables $\overline{A}(k)$ and $s(k)$ for each operational point we obtain a pair of values, which one can present in the diagram of turbine integral characteristics.
\[ A_o = \frac{1}{m} \sum_{k=1}^{m} A(k) \quad S_o = \frac{1}{m} \sum_{k=1}^{m} s(k) \quad C_o = A_o \cdot S_o \] (8)

\( m \) is the number of observation windows. The values of the above mentioned quantities are presented in Fig. 5. Variables \( A_o \) and \( S_o \) represent space-average grey level intensity and its respective fluctuation in the observed field. The variable \( C_o \) is introduced indirectly to prevent the influences of time stationary optical non-homogeneities on the observed rotor-blade.

From the Fig. 5 it can be seen that parameters \( A_o, S_o \) and \( C_o \) increase significantly with the increase of cavitation and predict the cavitation, as well. In comparison to the efficiency curve \( \eta \), parameters \( A_o, S_o \) and \( C_o \) detect cavitation from the very beginning at transfer from the point b to point c.

Fig. 5: Integral cavitation characteristics of the model turbine.

Fig. 6a: Cavitation structures at different operational points (a to f).

Fig. 6b: Scalar function \( \bar{A}(k) \) at different operational points (a to f).

Fig. 6c: Scalar function \( s(k) \) at different operational points (a to f).
From Figs. 6a, 6b and 6c one can notice that cavitation at transfer from operation points a to f increases monotonously and progresses from the area of the inlet blade edge to a surface cavitation which expands along the entire blade surface. Cavitation is more intense in the region near the channel wall. Topological structures of time-averaged grey level $\bar{A}(k)$ and respective standard deviation $s(k)$, depicting space fluctuation of cavitation structure are significantly different. Positions of the extrems of the variable $s(k)$ are along the flow shifted along the solid blade surface and identify the regions on the blade where cavitation structure characteristically pulsates. From former studies of cavitation on a single hydrofoil [7, 8] it can be concluded that that are already potential locations of cavitation erosion on a blade surface.

5. Installation of visualization system into the real object

One of the final goals at development of cavitation monitoring expert system in hydraulic machines is the installation of visualization system in the flow tract of Kaplan turbine. As an example, the first installation of a prototype monitoring system on power plant Doblar II is presented along with important installation phases which influence significantly on quality of visual information and consequently on the applicability of the complete cavitation monitoring system. Since the developed method is to be installed in the existing flow tracts of turbines and since above all the suction side of rotor blades are wanted to be observed, selection of proper location for the installation of the illumination and camera is limited.

In order to check in advance the area of the runner that can be illuminated resp. observed from a window installed (preferably in an inspection door) a 3-dimensional CAD model of the runner and the draft tube was developed (Fig. 7). On this model the blade visibility for different positions of the optical apertures can be checked before the real adaptations are made. The structure of the model is based only on few basic design data of the turbine. Thus it is easy to adjust the model to different turbines.

![Fig. 7: CAD model of the runner and the draft tube](image-url)
In Doblar II power plant, the illumination system and camera are installed in the inspection door about D/2 under the turbine rotor, where D is a rotor diameter. In Figs. 8 and 9 the improvised installation of a reflector of 110 lux and analogue camera with asynchronous reset are presented. In order to be able to observe sufficient wide visual field comprising suction side and the inlet edge of the blade, on the inspection windows plan-parallel optically transparent prisms made of plexi-glass where mounted. They enable inspection of turbine blade during turbine operation. Analogue camera was synchronised with rotational speed of turbine rotor. In Fig. 10 the image sample of a part of rotor blade during operation is presented. Image quality of the obtained digitised images is lower than at model observation on the laboratory test-rig, since on real object the turbidity of water, problems with homogeneous illumination and problems on account of significantly higher distances between the observed blades and camera have to be dealt with.

Further work is directed to a development of the rotor blades illumination system (higher illumination power and modified frequency characteristic of a light source), modification of prisms and selection of proper optics.

6. Conclusions

In the paper cavitation structures quantification with aid of computer-aided visualization method is presented. The method was applied on the model of the Kaplan turbine. At selected integral turbine parameters topological cavitation structures on the draft side of rotor blade were analysed. The computer-aided visualization method enables determination of with integral parameters varied cavitation regions. The respective fields of scalar function $\bar{A}(k)$ and standard deviation $s(k)$ were calculated. They depict the intensity of cavitation and dynamics of cavitational structure. The comparison of time-averaged values $A_\sigma$, $S_\sigma$ and $C_\sigma$ versus cavitational number $\sigma$ is presented. The presented method demonstrated its ability to be one of the best possible monitoring methods for the monitoring of cavitation on the experimental test rigs of water machines. In contrast to other methods it enables direct observation and quantification of cavitation on vital parts of turbo-machinery in time and space.

When extending the presented study on simultaneous signal analysis such as: pressure pulsations, mechanical vibrations, acoustic emission, and cavitational structures dynamics in the turbine flow field, the physical cavitational models of turbo-
machinery can be developed. The acquired knowledge can later be employed in power plant turbines. With aid of suitable equipment modification, the method can be used as a monitoring method on power plant water turbines. In the concluding part of the paper the installation of prototype visualization equipment for cavitation monitoring on a rotor of water turbine is presented. The installation problems that have to be dealt with are presented along with their solutions.

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