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AMERICAN JOURNAL OF HYDROPOWER, WATER AND ENVIRONMENT SYSTEMS

Editorial

Demand for electricity is increasing rapidly in Latin America. Expanding and enhancing the current power generation infrastructure is thus a major concern for the region. In that context, renewable energy is bound to play a relevant role in the coming years and hydroelectric energy especially so in view of its relatively unexploited potential, which is estimated in around 690,000 MW in the region.

Our mission is to contribute to the regional integration by means of the production of knowledge in the field of hydroelectric power generation and hydromechanical systems, with focus on technological advance and the rise of quality standards, but with an eye on the priorities of a region where, well into the XXI century, millions of people find themselves deprived of electricity. That includes the topics such as the evaluation of the development of projects of low environmental impact, the role of hydroelectric powerplants in the face of the diversification of the energy matrix as well as mini- and small-hydro projects to meet the demand of areas with no access to the electrical network.

Three symposia have been held and six editions of this Journal have been published since the creation of this, the Latin Group, in 2012. Added to that are postgraduate courses and exchange programs that are being organized at present. Mexico, Brazil, Ecuador, Colombia, Uruguay and Argentina are the most active members of the Group and it is our goal to get more involved in the future.

We firmly believe in the ability of our universities to conduct the research in the field of hydraulic turbomachinery and that this knowledge will have a beneficial impact on the policy making of our countries, whether on matters related to existing infrastructure as well as the development of long-term projects and strategies.

We understand that keeping and strengthening the link between the nations currently participating is a major challenge in the framework of a constantly evolving reality, seen reflected in the availability of economic resources, the technological tools and the swings of institutional management. May this new edition of the Journal serve as evidence that, however difficult, such challenge is achievable.

Eng. Sergio O. Liscia
Presidente Latin Group 2017-2021

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All papers must be submitted in English. In case the author wants to translate the article through the journal all costs for the translation will be charged on the account of the author.

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Divide your article into clearly defined and numbered sections. Subsections should be numbered 1.1 (then 1.1.1, 1.1.2, ...), 1.2, etc. (the abstract is not included in section numbering). Use this numbering also for internal cross-referencing: do not just refer to 'the text'. Any subsection may be given a brief heading. Each heading should appear on its own separate line.

1.1.2 Format

All text of the manuscript must be located within a 170 mm by 252 mm rectangle of a white A4 page or within 170 mm by 240 mm for the letter format. The margins are given in Table 1. An example of the page format is given in Fig. 1

[Table 1]: Page margin for manuscripts.

Margin Position	Top	Bottom	Left	Right
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All text should be single spaced, black and in 12-point type. "Times News Roman" or a similar proportional font should be used. Total length 15 pages in Word.

The terminology given in the *IEC Technical Report for the Nomenclature of Hydraulic Machinery* is recommended.

Introduction

State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

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Provide sufficient details to allow the work to be reproduced. Methods already published should be indicated by a reference: only relevant modifications should be described.

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A Theory section should extend, not repeat, the background to the article already dealt with in the Introduction and lay the foundation for further work. In contrast, a Calculation section represents a practical development from a theoretical basis.

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Results should be clear and concise.

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This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

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The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

References

Within the text, references should be cited in numerical order according to their order of appearance. The numbered reference citation within text should be enclosed in brackets.

After the second edition all papers must have at least one reference of the American Journal of Hydropower, Water and Environment Systems.

Example: It was shown by Prusa [1] that the width of the plume decreases under these conditions.

In the case of two citations, the numbers should be separated by a comma [1,2]. In the case of more than two references, the numbers should be separated by a dash [5-7].

List of References. References to original sources for cited material should be listed together at the end of the paper; footnotes should not be used for this purpose. References should be arranged in numerical order according to the sequence of citations within the text. Each reference should include the last name of each author followed by his initials.

(1) Reference to journal articles and papers in serial publications should include:

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Sample References

- [1] Ning, X., and Lovell, M. R., 2002, "On the Sliding Friction Characteristics of Unidirectional Continuous FRP Composites," *ASME J. Tribol.*, 124(1), pp. 5-13.
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Abstract

A concise and factual abstract is required. The abstract should state briefly the purpose of the research, the principal results and major conclusions. An abstract is often presented separately from the article, so it must be able to stand alone. For this reason, References should be avoided, but if essential, then cite the author(s) and year(s). Also, non-standard or uncommon abbreviations should be avoided, but if essential they must be defined at their first mention in the abstract itself.

Keywords

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'of'). Be sparing with abbreviations: only abbreviations firmly established in the field may be eligible. These keywords will be used for indexing purposes.

Abbreviations

Define abbreviations that are not standard in this field in a footnote to be placed on the first page of the article. Such abbreviations that are unavoidable in the abstract must be defined at their first mention there, as well as in the footnote. Ensure consistency of abbreviations throughout the article.

Acknowledgements

Collate acknowledgements in a separate section at the end of the article before the references and do not, therefore, include them on the title page, as a footnote to the title or otherwise. List here those individuals who provided help during the research (e.g., providing language help, writing assistance or proof reading the article, etc.).

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Present simple formulae in the line of normal text where possible and use the solidus (/) instead of a horizontal line for small fractional terms, e.g., X/Y. In principle, variables are to be presented in italics. Powers of e are often more conveniently denoted by exp. Number consecutively any equations that have to be displayed separately from the text (if referred to explicitly in the text).

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HYDRODYNAMIC BEHAVIOR ON KAPLAN TURBINES: EXPERIMENTAL METHODOLOGY FOR THE EVALUATION OF CAVITATION DEVELOPMENT BASED ON DYNAMIC MEASUREMENTS

¹Rivetti, Arturo; ¹Angulo Mauricio A.; ¹Lucino Cecilia V.; ²Botero Francisco.; ¹Liscia, Sergio O.

ABSTRACT

The gap between the discharge ring and the tip blade of Kaplan turbines favors the formation of tip vortices in which cavitation tends to develop even at Sigma plant values. The volume and location of such vortices vary with both the blade pitch angle and the gap size.

Under overload operating conditions, the intensity of tip vortex cavitation rises and its consequence is twofold: on the one hand, erosion at the discharge ring and runner blades; on the other hand, mechanical vibration and cracks on the stationary parts of the turbine. Furthermore, the resulting erosion pattern (consisting of as many eroded patches as guide vanes) suggests that tip vortex cavitation could be modulated by the number of guide vanes wakes.

In this work, a methodology is presented for the evaluation of the hydrodynamic behavior of Kaplan turbines based on dynamic signal processing. An experimental layout (including the instrumental consisting of accelerometers and a hydrophone) for physical models was proposed and tested.

The location of the sensors, sampling characteristics and signal processing, as detailed herein, are capable of describing the dynamic response of the turbine, characterized by the point that signals the onset of cavitation and its intensity. The dependence of cavitation on slight deviations of the geometry of the blades was also investigated.

KEYWORDS: cavitation, turbines, hydrodynamic.

1. INTRODUCTION

Kaplan turbines present a particular dynamic behavior, in which tip blade cavitation plays a very important role, especially at high loads. The most harmful effects that can occur are excessive vibration level and cavitation erosion on the blades and, in some cases, can also compromise the structural integrity of the discharge ring. These damages impact on maintenance costs and eventually also on the productivity of the plant because of power output limitations generated to preserve the units. Experimental studies on the dynamic behavior of Kaplan turbines are scarce when planning diagnostic tests [1, 2, 3], so the authors intend to share some methodological orientations, result of the experience accumulated in the matter and with the theoretical-conceptual support that validates them.

Pressure pulsations, vibration and acoustic emission can account for the degree of aggressiveness of the cavitation and its incipient Sigma condition with particular sensitivity in model tests, provided that the sampling frequency and signal processing techniques are appropriately chosen. An adequate processing of the dynamic signals allows detection of other phenomena of interest as well, like the modulation by typical frequencies, i.e. the passage of the blades and the corresponding rotor – stator interaction phenomena.

Although the question of scalability of dynamic behavior from model to prototype needs to be carefully studied, it is possible to get a good diagnosis of hydrodynamic phenomena in model for predictive purposes, since it has been possible to verify its validity by means of measurements on prototype turbines of high output, homologous to the models tested.

This paper deals with the question of what to measure, how to acquire the signals (suitable instruments and frequencies of

acquisition), where to install the transducers and how to process the information obtained in order to get a general description of the main aspects involved in hydrodynamic behavior of Kaplan turbines, mainly related to cavitation development at overload condition.

2. CONCEPTUAL FRAME

The potential energy contained in a cavitating flow is defined by eq.1 [4], as a function of the cavity volume and the difference of the surrounding and vapor pressure. When the cavity collapses, this energy is liberated producing shock waves, micro jets formation and vibration. The potential of erosion is then proportional to the amount of energy available for the collapse.

$$E_p \sim V_{vap}(p_\infty - p_v) \quad (1)$$

Where E_p = potential energy of the cavitating flow, V_{vap} = vapor volume, p_∞ = Surrounding pressure, p_v = vapor pressure.

As cavitation number σ decreases, cavitation develops mainly as tip leakage cavitation. The interaction of tip cavitation volume with guide vanes wakes produces cavitation collapse at fixed spots over the discharge ring (Fig 1). The location of this spots and the dynamics of each cavity depend of the rotational speed ω , and the number of guide vanes (Z_0) and runner blades (Z_b).

The influence of the non-uniform flow leaving the guide vanes can be identified by the analysis of the modulation process generated by the stationary flow field of the 24 guide vanes, and the rotating flow field due to the 5 runner blades, as proposed by Ruchonnet et al. [5]. Table 1 shows the RSI patterns for several orders of harmonics for the first

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diametrical mode number k_1 . The highest amplitude expected is for the first order of harmonics of flow through the guide vanes ($n = 1$) and the fifth order of harmonics of flow through the runner ($m = 5$), since k_1 is the minimum in absolute value ($k_1=1$). The characteristic frequency of $25 f_n$ (where f_n is the runner rotation frequency), given by the expression $f/f_n = mZ_b$, has to be present if the interaction exists.

[Table 1]: First diametrical mode number k_1 according to harmonic order m for the runner blades ($Z_b=5$) and for the guide vanes ($Z_g=24$).

n/m	$k_1=mZ_b-nZ_g$				
	1	2	3	4	5
1	-19	-14	-9	-4	1
2	-43	-38	-33	-28	
3	-67	-62	-57	-52	-47

3. METHODS AND MATERIALS

3.1. Experiments

Experiments were performed at the Laboratory of Hydromechanics of the National University of La Plata, Argentina. The test rig is a closed circuit that allows for the testing of Kaplan and Francis turbines (Fig. 2). The model test was carried out in compliance with the IEC 60193 standard [6]. The error estimated for the hydraulic efficiency is less than 0.24 %.

The scale model was a five-blade Kaplan turbine with twenty-four stay and guide vanes. Its diameter was $D = 340$ mm and its specific speed was $ns = 614$. The rotational speed during the test was $n = 1000$ rpm, which yields a Reynolds number of $Re = 6.05 \times 10^6$, based on the blade tip velocity. The model was placed in the test rig between the high- and low-pressure tanks. The head was adjusted by varying the rotational speed of the recirculation pump. The low-pressure tank is equipped with a vacuum pump and a pneumatic controlled valve allowing for the variation of the absolute pressure of the system, in order to set the desired σ , given by equation 2.

$$\sigma = \frac{\left(\frac{p_b - p_v}{\gamma}\right) + h_s + Ec_2}{H} \quad (2)$$

Where p_b = pressure at low-pressure tank, p_v = vapor pressure, γ = water specific weight, h_s = suction head, H = net head, Ec_2 = Kinetic energy at the draft tube outlet. Given

that the test was carried out at constant head, flow rate and rotational speed, it becomes apparent from Eq. 2 that can be modified only by varying the pressure at the low pressure tank.

3.2. Monitoring system

Acceleration measurements: Three Endevco Isotron 7259B accelerometers, with a flat frequency response from 0.1 Hz to 30 kHz, were placed at the discharge ring (Fig. 3). The typical resonance frequency is 90 kHz. The AC1 is located above the centerline of the runner; the AC2, on the blade passage plane; and the AC3, at the draft tube inlet.

Noise emission: One Brüel & Kjær type 8104 was located downstream the center-line at a distance of $1.0 D$ immersed in water.

Keyphasor: An inductive sensor Balluff BES00JY together with a cog in the shaft was implemented to obtain the runner passage key.

Data acquisition: Dynamic signals were simultaneously sampled with a 16-bit resolution at a 35 kHz sampling rate during 40 seconds for every measured point. Data sampling and post-processing were performed with software developed by LABVIEW.

3.3. Operational condition and test proceeding

An operational point of high load for the nominal head corresponding to the prototype machine was chosen for the experiment. This point corresponds to an ON CAM combination.

For this condition, the speed factor [6] was $n_{ED} = 0.769$ and the discharge factor [6] $Q_{ED} = 0.589$, where

$$n_{ED} = \frac{nD}{\sqrt{gH}}; \quad Q_{ED} = \frac{Q}{D^2 \sqrt{gH}}$$

Only the cavitation number was modified by adjusting the absolute pressure in the low-pressure tank covering a range going from $\sigma = 2.40$ (no cavitation) to $\sigma = 0.919$ (full developed cavitation).

A series of tests were performed wherein the cavitation number was swept over the range 0.919-2.40 in a stepwise manner. The upper limit corresponds to a cavitation-free operating condition. The cavitation number is decreased by gradually diminishing the pressure of the test rig circuit. A total of seven steps were considered until cavitation was fully developed. For every step the acceleration signal and the test rig state variables were acquired during 40 seconds.

3.4. Data processing

The suitable selection of sensors and its location as described above play a major role in the diagnostic assessment of tip vortex cavitation. Said phenomenon leaves a trace that can be unveiled both in the time and frequency domains. On the one hand, the proper parameters of the turbine design influencing the formation of vortices, such as number of blades, blade clearance and discharge ring, and permissible tolerances for manufacture, become sources of spectral components of the rotor frequency. On the other hand, the formation and subsequent implosion of vapour cavities become a source of wide-band noise. In addition, interactions among them and the interaction between fluid and structure (FSI) provide a plentiful mine to be exploited [7].

3.4.1 Time domain

The time-domain analysis for rotating turbomachinery can provide meaningful geometric and synchronous information if it is assumed that samples came from normal distributions; i.e., normal variables. In that sense, two types of strategies are proposed: inter-condition and condition-dependent analysis. Traditional estimators such as the variance (Eq. 3) and the root mean square value (*rms*, Eq. 4), provide an overall measure of the variable x that can serve as an indicator for comparing different operating conditions. In fact, they indicate if the variable increases or decreases, globally, when the machine goes from one condition to the next (inter-condition). Here, x is understood as a series of N samples, successive, equally spaced and indexed in time order; each sample denoted by x_i . In the particular case of time series of zero mean ($\bar{x}=0$), the *rms* value is equivalent to the standard deviation, which in turn is the square root of the variance.

$$var = \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2 \quad (3)$$

$$rms = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2} \quad (4)$$

An estimation of the mean behavior of a random variable, during one shaft's revolution, can be obtained averaging several (more than thirty) phased time-series samples of one revolution [8]. A review of Time Synchronous Average (TSA) algorithms was published by Bechhoefer and Kingsley [9].

Concisely, in our work it consists of: key phasor marks are used to index the time-ordered samples corresponding to one revolution length. An estimation of the variance is recovered by calculating the sample variance of the same set of time series (several revolutions of the rotor). Then a representation of the average revolution bounded by its confidence intervals can be plotted as a function of time, angular position or any other scale. Balanced fluctuations with constant variance are expected from a machine in good condition; if strong bumps or fluctuations in variance are observed, it is a sign of a defect located on the rotor oriented according to the horizontal scale used for the plot and the key phasor mark (condition-dependent analyses). Protuberances with low or constant variances can be explained by hydraulic, mechanical or electrical synchronized imbalances. High variance can be associated to stochastic phenomena like cavitation formation and implosion.

3.4.2. Frequency domain

Once cavitation incepts, the generated wide-band noise propagates from the collapsing bubbles, through the fluid, to the structure. This noise can be perceived as a global increase of the rms value of the collected signal, as stated above, but also as an energy pattern less rise-up along several thousand Hertz since it is wide-banded. For this reason, conventional representations in the frequency domain as the amplitude spectrum or the power spectrum are not the best tools for the detection of cavitation. In general, such analyzes are not suitable for the technical diagnosis of stochastic phenomena.

Therefore, assuming that the dynamic transducer is installed in the stationary frame of a Kaplan turbine, then the recorded noise intensity coming from a cavitating vortex attached to the tip of the rotating runner blades varies periodically depending on the distance measured from the tip of the blade to the monitoring point. Such effect produces the modulation of the noise at a multiple of the impeller blade passing frequency. That is to say, the noise emitted by the implosion of the bubbles becomes more and less intense in a harmonic way, as the rotating blade with the anomaly approaches or moves away from the sensor.

This sort of modulation has two desirable characteristics that can be profit from the technical point of view: the first is that instead of only one carrier frequency, there is a wide band of carrier frequencies; the second is that carrier frequencies may extend up to the highest sampled frequency. In other words, the information is carried by several frequency channels, and many of these channels are free of interference produced by other sources since their frequencies are high enough (several thousand hertz). Consequently, there are bands in the frequency domain where symptoms of tip vortex cavitation are preserved.

The demodulation technique described by Escaler et al. [10] is adopted to process the fluid and structure-borne. This technique has proven to be successful in diagnosing other manifestations of cavitation [7], [11]. A simplified scheme of required processing is shown in Figure 4.

[Figure 4: Demodulation processing.]

In brief: (a) band-pass filter is applied to the signal. Fourth to ninth order Butterworth Infinite Impulse Response digital filter is a suitable choice. Low cutoff frequency is set above the maximum expected harmonic of the rotating speed; for most cases it is around 180fn. High cutoff frequency can be set just below the antialiasing bandwidth limit. A pre-centering is highly recommended, especially if the data acquisition system especially if the equipment lacks a capacitive coupling circuit (AC). Arithmetic mean of the signal is subtracted from every sample, Eq. (5). (b) The analytic signal is assembled with the filtered signals as real part and its Hilbert transform as the imaginary part; as it is complex valued, therefore it can be expressed in exponential notation. The Hilbert transform actually leads to the harmonic conjugate of the signal. (c) The modulated signal is the envelope of the analytic signal, i.e. the instantaneous amplitude and can be extracted as its modulus. (d) Centering the resulting signal by subtracting its arithmetic mean; see equation (3). Finally, the centered envelope is transformed from the time domain to the frequency domain in order to extract its respective harmonic components and rms amplitudes. This transformation can be achieved by applying the Fast Fourier Transform (FFT), which is a very efficient algorithm to decompose discrete time series

$$\tilde{A}(t) = A(t) - \bar{A}(t) \quad (5)$$

It is expected that in the presence of tip vortex cavitation the most prominent frequency component corresponds to the passage of blades or one of its harmonics. On the contrary, a flat or decadent spectrum is anticipated.

4. RESULTS

4.1. Time domain

[Figure 5: TSA processing of the signal capture by the accelerometer (left) and signal capture by the hydrophone (right) at E05 ($\sigma=1.229$). The graphs at the top show a one second fragment of the raw measured signal. The bottom graphs show the average signal plus and minus its variance for a revolution. The domain identifies the passage of each of the blades of the impeller.]

The result of applying the introduced TSA procedure is presented in Figure 5. For this case, the operating point E05 ($\sigma=1.229$) was selected because it allows to show several advantages of the method. The graphs at the top show a fragment of a second of each of the raw signals, i.e. accelerometer (left) and hydrophone (right). The graphs at the bottom show the result. In the case of the accelerometer signal, the contribution that is made by superimposing the variance is evident; for each blade passage at least the twenty-fifth synchronous component is identified, not to mention the other attributes such as a fluctuation of the amplitude and the large magnitude of the variance compared to the average value of the acceleration. For the hydrophone, it can be observed something different. The variance is relatively low with respect to the variation of the acoustic pressure and therefore it is possible to identify the twenty-fifth harmonic, even from the averaged signal. Additionally, it is interesting to note, as each blade passes, on average, manifests a particular behavior, which could be associated with geometric tolerances of the machine.

4.2. Frequency domain

[Figure 6: Amplitude spectrum of the envelopes for accelerometer (a) and hydrophone (b). Frequencies are presented as multiples of the rotating frequency of the shaft. Every spectral vector corresponds to a specific sigma value. Tip vortex cavitation was firstly observed at E03 ($\sigma=1.488$); this is consistent with the arisen of the spectral component 25fn. Nevertheless, the hydrophone allowed to observe more details and even, to detect the said phenomenon in conditions of extreme cavitation like E06 ($\sigma=1.036$) and E07 ($\sigma=0.919$).]

The signals that were collected with the accelerometer and the hydrophone were demodulated following the procedure

previously described and presented in a specific way. Each envelope was spectrally decomposed and the domain normalized with the frequency of shaft of the machine to be presented as orders of that frequency. Then, the spectra of all the operating points were ordered on a 3D chart based on the operating point, that is, as a function of the sigma value. The results are shown in Figure 6. According to the high speed images taken at each operating condition, it was determined that the tip vortex cavitation first appeared at E03 ($\sigma=1.488$) and thus, ascending to E07 ($\sigma=0.919$), where in addition other types of more violent cavitation were observed. This correlates quite well with the manifestation of the spectral component 25fn in signals, accelerometer and hydrophone. However, it should be mentioned that once the hydrodynamic inside the machine is sufficiently intemperate, as in E06 ($\sigma=1.036$) and E07 ($\sigma=0.919$), the accelerometer stops perceiving the said frequency.

5. CONCLUSIONS

The tip vortex cavitation that develops at lower cavitation numbers was singled out as one of the main causes of the increase of vibration levels.

The analysis of the signal of the hydrophone reveals the presence of RSI-related phenomena which becomes apparent when tip vortex cavitation develops.

Both, the accelerometer and the hydrophone, allow detecting with sufficient sensitivity the manifestation of tip vortex cavitation. However, the hydrophone is able to detect it even under the interference of other phenomena, including other types of cavitation.

The 25fn spectral component of the envelopes was identified as a powerful indicator of tip vortex cavitation. This same component stood out differently in the results of the TSA. For the case of the accelerometer, it became more noticeable thanks to the superposition of the variances, whereas for the hydrophone, it became evident even from the average signal of the acoustic pressure.

The TSA results revealed a variation in the amplitude of the fluctuations corresponding to the passage of each impeller blade. This is attributed to the geometric tolerances of the model. In addition, it allowed to observe the component 25fn that later was associated with the cavitation.

The methodology presented in this paper could be easily applied on prototype since the use of accelerometers is a non-intrusive procedure.

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