CLASSIFICATION OF CAVITATION IN HYDRAULIC MACHINES USING VIBRATION ANALYSIS

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ABSTRACT

This paper describes vibration analysis techniques that have been adapted and used to classify cavitation in a model Francis turbine. This analysis can be used to compliment standard cavitation tests.

Cavitation can be classified in various ways using vibration analysis. Cavitation attached to the blades of the runner is modulated by instabilities caused by the interaction with the blades and the guide vanes, as well as by the outlet swirl. The shape of this modulation is not sinusoidal. Cavitation on the runner is non-uniform; i.e. some blades are, on average, experiencing more aggressive cavitation than others are.

Analysis techniques employed include a demodulation technique that considers the envelope auto-power spectrum, joint time-frequency analysis and phase averaging.

RÉSUMÉ

Le présent papier présente des techniques d'analyse vibratoire qui ont été adaptées pour la classification de la cavitation dans un modèle de turbine Francis. Cette analyse pourrait être utilisée pour compléter les essais standard de cavitation.

La cavitation peut être classifiée de diverses façons au moyen de l'analyse vibratoire. La cavitation attachée aux aubes de la roue est modulée par les instabilités causées par l'interaction rotor-stator, ainsi que par le tourbillon en sortie de roue. De telles modulations ne sont pas harmoniques. La cavitation sur les aubes n'est pas uniforme, i.e. certaines aubes subissent, en moyenne, une cavitation plus agressive que d'autres.

Les techniques d'analyse utilisées englobent l'analyse spectrale, l'analyse temporelle et fréquentielle, la démodulation à haute fréquence ainsi que la moyenne de phase.

INTRODUCTION

Cavitation monitoring of hydraulic machines is useful for manufactures, end-users and researches alike. It has the application for model and prototype turbine acceptance tests, optimisation of prototype operation, upgrades and modifications as well as a research tool in the study of fluid machinery. This paper describes vibration analysis techniques that have been adapted and used to classify cavitation and quantify its relative aggressiveness. Results from a model Francis turbine are used as an example. A more detailed account on this topic has recently been published (Ref. 1).

EXPERIMENTAL

A measurement campaign was undertaken in order to investigate the cavitation characteristics of a Francis turbine. The turbine consisted of a small prototype runner mounted in a model casing. Turbine and flow condition details are shown in Table 1. Testing was carried out on the model test rig at LMH (Ref. 2).

Vibration measurements were made during a standard cavitation test. This consists of investigating the influence of cavitation development on the hydraulic characteristic of the turbine, and in evaluating the erosion risk. Visual observations of cavitation behaviour can be made through the transparent draft tube using a stroboscope. At various flow conditions the cavitation parameter (sigma) is reduced and the efficiency curve obtained.

High frequency accelerometers were mounted close to the guide bearings and above two guide vanes, one closest to the volute tongue and the other 112^{o} to this (Fig. 1). Measurements made at the guide vane prove to be the most useful for classifying cavitation.

Vibration signals were first band-pass filtered in the range 40–50 kHz, which includes the frequency range of cavitation-induced vibration. The envelope of this signal was determined using analogue demodulator prior to data acquisition. This allows the acquisition of long signals containing many revolutions of the shaft, with no loss of information important for analysis. A once per revolution taco signal was also acquired as a reference.

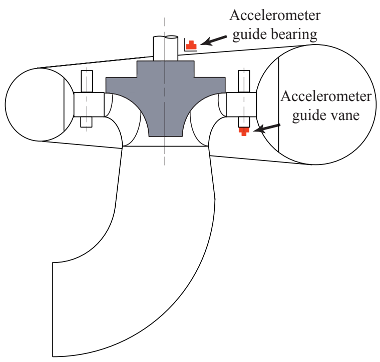


Fig. 1 Transducer Locations

Number of Blades	13
Number of Vanes	16
Nominal Head	88m
Nominal Power	400 kW
Nominal Flow	0.54 m^3/s
Nominal Shaft Speed	1000 rpm
Test Condition Head	88m
Test Condition Power	467 kW
Test Condition Flow	0.64 m^3/s
Test Condition Shaft Speed	500 rpm
Test Condition Sigma	0.07

Table 1 Turbine and flow condition details

TECHNIQUES USED FOR CAVITATION ANALYSIS

Demodulation - Envelope Auto-Power Spectrum

In hydraulic machines, unstable cavitation leads to erosive cavities being shed off the blades. The shedding frequency is governed by the cavitation interaction with flow instabilities. These are generated by the passage of blades through the wakes of the guide vanes or the spiral case tongue, as well as by hub vortex oscillation (outlet swirl). The shedding frequency is forced to a frequency characteristic to the machine, e.g. blade passing frequency (b.p.f., i.e. number of blades multiplied by rotational speed), guide vane frequency (g.v.f. i.e. number of guide vanes multiplied by rotational speed) or swirl frequency. A peak in the envelope auto-power spectrum at the characteristic frequency detects modulated vibration (Refs. 1, 3 & 4).

Large errors are present in vibration amplitude values due to losses in the electrical enveloping circuit and the high frequency sensitivity of the accelerometers. However values are quoted as engineering units for convention and are still useful for comparison purposes.

Joint Time Frequency Analysis

By its nature cavitation is not steady. The demodulation technique does not attempt to characterise non-uniform and intermittent cavitation. Non-uniform cavitation has a differing cavitation severity on the blades. Intermittent cavitation changes in severity with time. Very strong but very intermittent cavitation may be more erosive than weaker but constant cavitation. This depends on the ability of the blade material to resist cavitation erosion. For a given material there will be a threshold of the cavitation intensity, below which, no erosion will occur, irrespective of the intermittence.

Joint time-frequency analysis (JTFA) analyses non-stationary signals and can be used to detect intermittent and non-uniform cavitation that could easily be missed, or the analysis be inconclusive, if only the power spectrum of the envelope is considered. The algorithm used is the Quadratic Short Time Fourier Transform (STFT).

Phase Averaging

Phase averaging is a useful technique that helps understand the interaction between blades and guide vanes of hydraulic machines (Ref. 5). Calculation of RMS values of vibration envelope samples covering many rotations of the runner is made. Results can be presented on a polar plot as a function of runner position. An accurate once per revolution taco signal is necessary to synchronise the start of each rotation.

INITIAL FINDINGS – ENVELOPE AUTO-POWER SPECTRUM

Interesting initial observations can be made about the auto-power spectra of the envelope signals, as shown in Fig. 2. The x-axis (frequency) is expressed in terms of harmonic of running speed. Many harmonics can be seen in the spectrum. As well as b.p.f. at 13x rpm, there are also peaks at 1, 12, 14, 15, 16, 17, 19, 20x rpm etc. and also at 0.3, 13.3, 14.3x rpm (Fig. 2a). In addition high amplitude harmonics at 13x (b.p.f.) and 16x (g.v.f.) seem to be repeated at 26x rpm and 32x rpm (Fig. 2b).

Clearly the presence of a peak at b.p.f. alone is not sufficient as an indication of the presence of cavitation. Further analysis and interpretation of the vibration signature is required to explain the significance of other peaks in the spectra, and so more fully explain the fluid phenomenon.

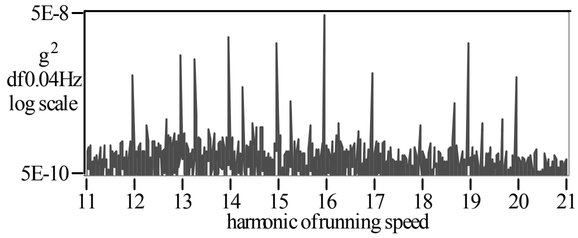


Fig. 2a Envelope auto-power spectrum (11-21x rpm)

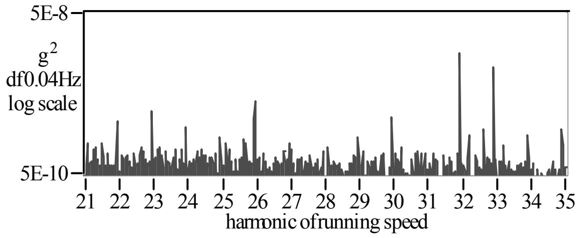


Fig. 2b Envelope auto-power spectrum^ (21-35x rpm)

CHARACTERISTIC FREQUENCIES AND NON-UNIFORM CAVITATION

It can be shown that the runner experiences non-uniform cavitation, i.e. some blades, on average, experience more aggressive cavitation than others do. This can be due to minor changes in dimensions due to manufacturing tolerances. Four techniques are used to reach this conclusion, and are described in detail below. Furthermore, the important characteristic frequencies are identified as the b.p.f. and g.v.f.

Double Envelope Demodulation

A double enveloping technique can be used to help detect non-uniform cavitation. The principle is similar to the demodulation technique described previously. The envelope signal is first filtered around the characteristic frequency, which filters out low frequency components. Next the envelope of this envelope is calculated digitally using Hilbert Transforms. Finally its auto-power spectrum is determined.

Fig. 3 shows the auto-power spectrum of the double envelope. A clear peak is seen at running speed, which shows that the vibration at b.p.f. also has a component at running speed. This could be due to non-uniform cavitation.

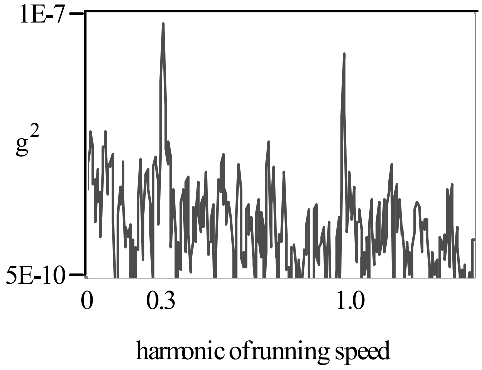


Fig. 3 Double envelope auto-power spectrum

Interpretation of the Envelope Auto-Power Spectrum

Non-uniform cavitation explains the presence of harmonics of running speed in the envelope auto-power spectrum (Fig. 2). This can be demonstrated by trigonometry.

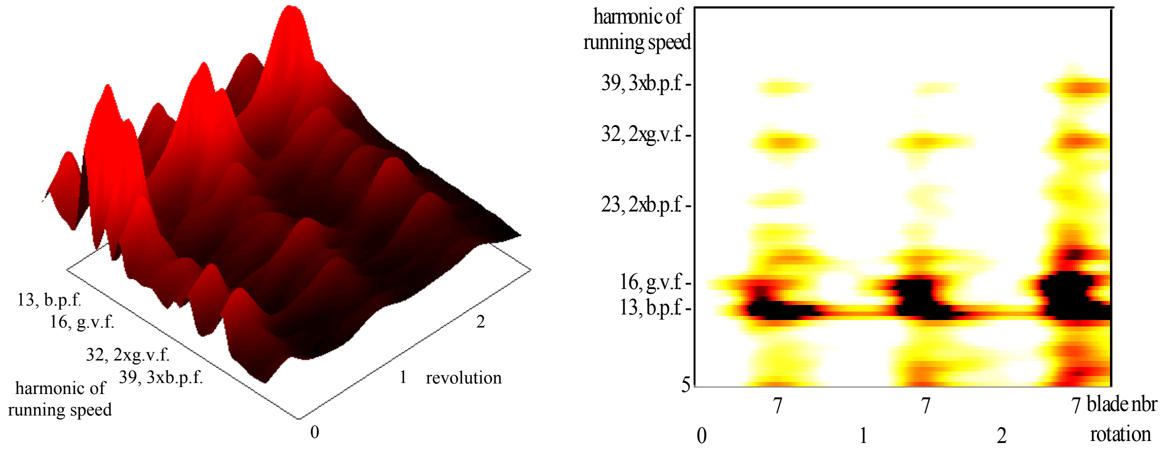
Average STFT Spectrogram

The average STFT Spectrogram for the selected flow condition is shown in Fig. 4 (three-dimensional and plan view). The plots cover 3 rotations of the runner. Initial observations of the plots show that the most prominent vibration intensity is localised in both frequency and time. It appears that the prominent intensity spans both b.p.f. and g.v.f. In time the vibration is localised around one particular blade.

Other harmonics at 2&3x b.p.f and 2x g.v.f. can also be identified in the spectrogram and are also localised in time. These can be seen more clearly in three-dimensional plot. Unlike the auto-power spectrum (Fig. 2), no other harmonics of running speed can be seen. This helps confirm that these harmonics are in fact due to the blades experiencing non-uniform cavitation, and are not characteristic frequencies themselves. The important characteristic frequencies for this turbine are the b.p.f. and g.v.f.

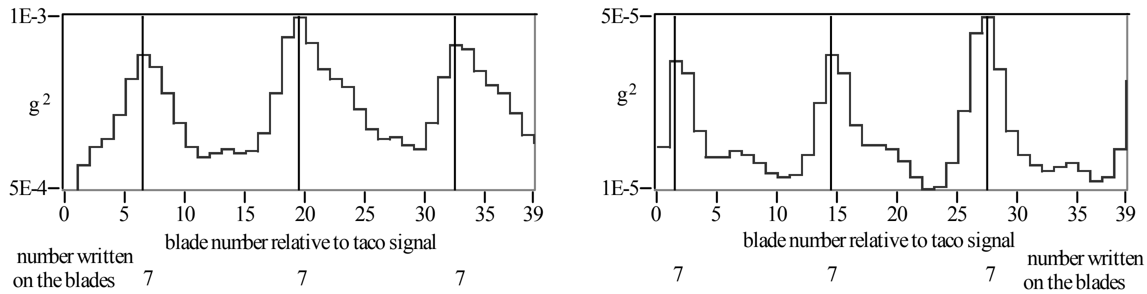
The average STFT Spectrogram coefficients at b.p.f. can be calculated and shown on a two-dimensional graph (Fig. 5). These again show the presence of non-uniform cavitation. Both locations at the guide vane show a clear repetition at running speed. At guide vane 1 (closest to the volute tongue) a peak is seen at blade 7 (relative to the taco signal). At guide vane 12 (112^{o} to the volute tongue) a peak is seen at blade 2. If the numbers written on the blades and taco position are considered, results from both measurement locations correspond to blade 7 (referring to the numbers written on the blades).

Note that it is difficult to accurately determine exactly which blade is experiencing the most cavitation, as each blade from leading edge to trailing edge covers a large portion of the runner angular position. This means for example that the leading edge of blade 7 has almost the same angular position as the trailing edge of blade 6.



a) Three dimensional view *b) plan view*

Fig. 4 Average STFT Spectrogram plot



a) Guide vane closest to volute tongue *b) Guide vane 112º to volute tongue*

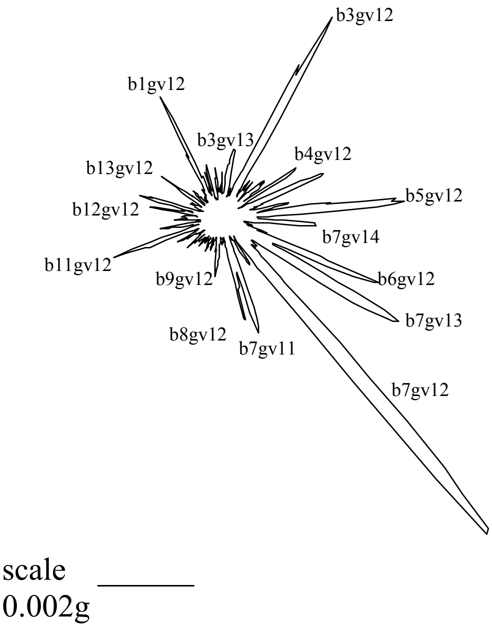
Fig. 5 Average STFT Spectrogram coefficients at b.p.f.

Phase Averaging

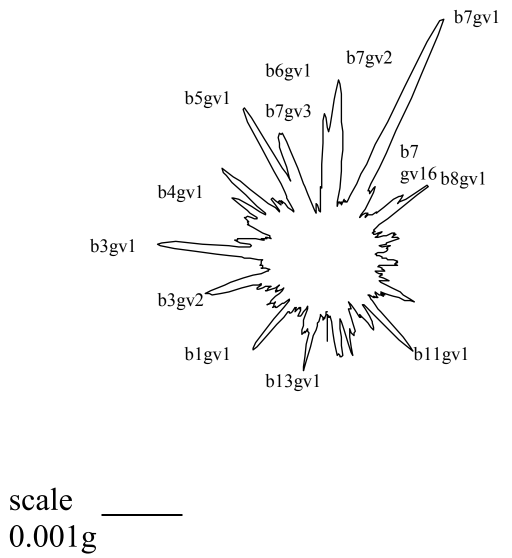
Fig. 6 shows phase average polar plots at the two guide vanes. The diagrams clearly show non-uniform cavitation behaviour. At both guide vanes, blade 7 (referring to the numbers written on the blades) experiences the most aggressive cavitation. In addition, cavitation can be detected with varying degrees of strength on blades 1, 3, 4, 5, 6, 7, 8, 11 & 13. This is consistent on both guide vane channels.

CAVITATION MODULATED BY OUTLET SWIRL

Often an outlet swirl exists in the draft tube that can rotate at around one third running speed. The presence of a swirl can be confirmed by visual observations through the transparent draft tube. During certain flow conditions the cavitation on the runner can be modulated by this swirl. This is evident by analysing data using four independent techniques described below.



a) Guide vane closest to volute tongue



b) Guide vane 112º to volute tongue

Note: b7gv12 means blade 7
(referring to the numbering on the blades)
interacting with guide vane 12 etc.

Fig. 6 Phase average polar plots

Closer Inspection of the Envelope Time Series

The modulation at swirl frequency can be seen in some cases by closer inspection of the envelope time series (Fig. 7). A clear repetition can be seen at a time interval corresponding to the frequency of the rotating swirl. Only very clear cases of modulation can be detected in this way.

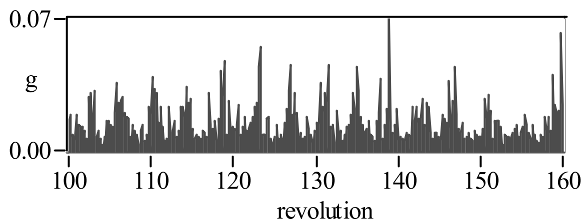


Fig. 7 envelope series

Interpretation of the Envelope Auto-Power Spectrum

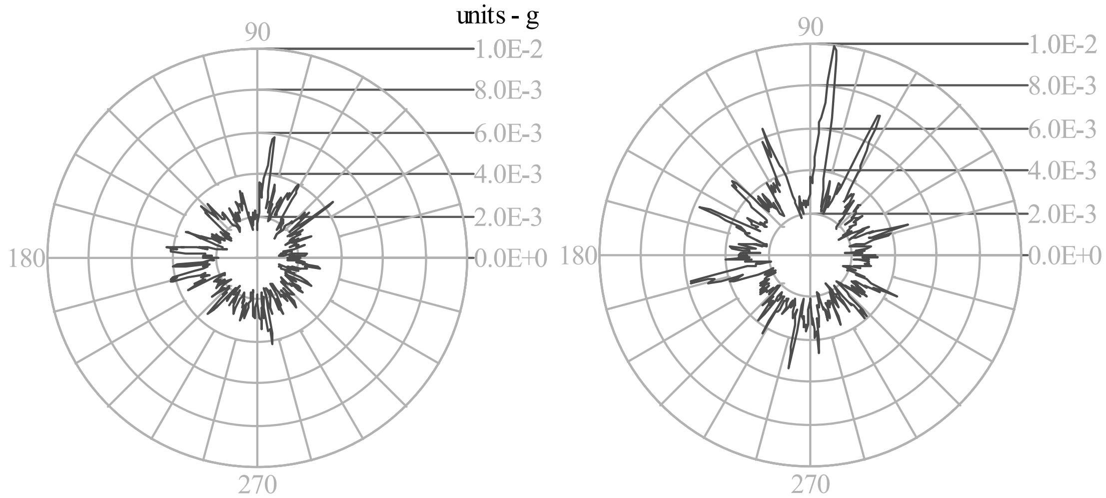
At some flow conditions the presence of side bands around b.p.f. can be seen in the auto-power spectrum. These side bands are displaced from the b.p.f. by the swirl rotational frequency (see Fig. 2). This phenomenon can be attributed to the swirl modulating the cavitation and can be explained using trigonometric.

Double Envelope Demodulation

Double envelope demodulation can be used to confirm if the cavitation on the blades is being modulated by the output swirl. A peak at the swirl frequency in the double envelope spectrum indicates modulation and can be seen in experimental results (Fig. 3).

Phase Averaging

If the cavitation is being modulated by the swirl, the magnitude of the induced vibration will rise to a maximum and fall to a minimum within one swirl cycle. This can be detected using phase averaging, by taking averages estimated to be in the same part of the swirl cycle. Fig. 8 demonstrates this. This change in amplitude is quite clear, the maximum amplitude of vibration is approximately twice the minimum.



a) maximum *b) minimum*

Fig. 8 Maximum and minimum values due to modulation of outlet swirl

INFLUENCE OF CAVITATION MODULATED BY ADJACENT GUIDE VANES

The influence of adjacent guide vanes on cavitation modulation can be investigated using phase averaging. Fig. 6 shows polar plots of phase averaged envelopes. As discussed previously there are peaks in the vibration as individual blades pass the guide vane where the accelerometer is mounted. In addition, there are other peaks at angles representing the guide vanes before and after the measurement location. This shows that the vibration caused by cavitation modulated due to the one guide vane, can be strong enough to be detected on the adjacent guide vane. This can be seen most clearly when blade 7 passes these guide vanes and is evident at both measurement locations. At guide vane 1 (closest to the volute tongue), the interaction between blade 7 and guide vanes 16, 1, 2 and 3 can be detected. At guide vane 12 (112^o to the volute tongue), the interaction between blade 7 and guide vanes 11, 12, 13 and 14 can be detected. Similarly the interaction between blade 3 and guide vanes 2 and 13 can also be detected.

This phenomenon explains why the guide vane frequency is a characteristic frequency for this machine as well as the blade passing frequency. It also confirms that each guide vane, not only the volute tongue modulates the vibration.

SHAPE OF THE MODULATION

In the envelope auto-power spectrum, the pattern of harmonics seems to be repeated at multiples of b.p.f. and g.v.f. (Fig. 2b). This was also seen clearly in the STFT Spectrogram

(Fig. 4). This can explain if the modulation forced by flow instabilities is not sinusoidal. In this case harmonics of the characteristic frequencies (i.e. b.p.f. and g.v.f.) will exist. The harmonics of running speed due to non-uniform cavitation will also be repeated. The spectrum of the combination of the two phenomena (non-uniform cavitation and the shape of modulation) is a convolution of the spectra of the two separate phenomena.

CONCLUSIONS

Vibration analysis can be used to characterise cavitation and complement standard model cavitation tests. For this turbine the cavitation can be characterised in the following ways: -

- Cavitation attached to the blades of the runner is modulated by instabilities caused by the interaction with the blades and the guide vanes as well as by the outlet swirl.
- The shape of this modulation is not sinusoidal.
- The cavitation on the runner is non-uniform.

ACKNOWLEDGEMENTS

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