Turbine Cavitation Diagnostics and Monitoring
Multidimensional and Simple Techniques

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The consequences of cavitation erosion are best assessed directly, during an overhaul. However, in order to find out from which operating points they stem and clarify the role various turbine parts play in cavitation, one must apply vibro-acoustic measurements or monitoring. Based on the example of the large Francis turbines at the Grand Coulee Dam in the USA, the multidimensional vibro-acoustic technique for cavitation diagnostics and monitoring is presented and compared to simple techniques.

1. Introduction

Due to the strong dependence of cavitation on the fine details of turbine geometry, turbines declared as identical, even when operated in identical conditions, may have substantially different cavitation characteristics. The fact that model tests cannot predict these differences makes a prototype-scale inspection of turbine cavitation necessary. While the final consequence of cavitation in the form of accumulated erosion can be assessed by direct inspection in an overhaul, on-line tests on prototype turbines are necessary in order to discover the origin of the deterioration effects and to answer questions such as which operation points contribute most, and which turbine parts cause the effects? Such tests in the form of permanent monitoring are essential in order to follow aging effects and detect changes due to incidents.

Cavitation in a prototype turbine can hardly be seen. Thus, the only practical manner to perform prototype-scale cavitation tests and monitoring is to use suitable vibro-acoustic sensors installed on suitable locations on a turbine and listen to cavitation noise or assess its consequences, such as the vibrations of turbine parts. Depending on the number of sensors and the methods used to analyze the signals they deliver, two classes of vibro-acoustic techniques for turbine cavitation diagnostics and monitoring can be distinguished: multidimensional and simple techniques.

Fig. 1: Grand Coulee Dam on the Columbia River in Washington state, USA: 6809 MW of installed generating capacity, 3x605 MW and 3x805 MW in the Third Powerplant.

In this paper, Korto’s multidimensional technique is presented and is compared to two simple techniques implemented in cavitation monitoring systems manufactured by two US companies. The comparison is based on the tests performed on the large Francis turbines at the Third Powerplant of the Grand Coulee Dam owned by the US Bureau of Reclamation (Fig. 1).

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2. Multidimensional technique

In order to avoid the worst consequences of cavitation, heavily loaded screw propellers behind bulky ship hulls are sometimes designed to operate in a fully developed cavitation flow. Nothing like this is practiced in hydro turbines. Here, cavitation is avoided or, in order to make the excavation works less expensive, it is accepted but is made rather weak. Thus, a typical turbine is usually operated close to the cavitation threshold. As a consequence, variations in the flow behind the stay vanes and guide vanes may be turning cavitation on and off on the runner blades as these pass through their wake. This results in the situation illustrated in Fig. 2.

Fig. 2 – Polar representation of the typical dependence of the short-time mean cavitation intensity (radial coordinate) on the runner’s instantaneous angular position (angular coordinate).

As far as cavitation is concerned, no two truly equal guide vanes and no two truly equal runner blades can be found in a turbine. This means that, instead of thinking about cavitation in the turbine as a whole, VxB independent cavitation processes may be expected to function in it, where V and B are the number of guide vanes and the number of runner blades, respectively. Data on these cavitation processes are to be sought in the curves like those in Fig. 2. There, different peaks describe the interaction of different guide vanes and different runner blades.

Fig. 3 – Curves such as those in Fig. 2 found in a Kaplan turbine in 12 different circumferentially distributed locations. Both the mean cavitation intensity and the forms of the curves differ substantially.

Fig. 4 – An example of the sensory system in a multidimensional diagnostic cavitation test.

Fig. 5 – Three cavitation mechanisms found in a turbine differ in cavitation threshold.
Checking dependences like these in different locations in a turbine, one finds strong differences (Fig. 3). They are consequences of variations in the guide vanes’ shape and setting and of irregularities in the spiral casing shape; even if these irregularities do not affect efficiency, they may have a strong impact on cavitation. Obviously, by means of a vibro-acoustical sensor in one location only, an arbitrary result is obtained, both concerning the estimation of the mean cavitation intensity and the information on the cavitation processes. In the multidimensional technique, a rather high number of sensors is used. A typical configuration for a diagnostic test is illustrated in Fig. 4; for permanent monitoring, the number of sensors is reduced.

In most cases, several types of cavitation appear in a turbine in the same or different operation conditions; an example is shown in Fig. 5. The same cavitation type can also appear in different locations within the turbine. Being generated in different flow segments, such different cavitation mechanisms are generally independent and should be dealt with as such. Furthermore, each of these mechanisms differs in details on each guide-vane/runner-blade pair. Denoting the number of cavitation mechanisms found in a turbine under consideration by M, one thus has M×V×B different processes to assess; for a typical Francis turbine, this may amount to 1,000. With the multidimensional technique, identification of different cavitation mechanisms is done by means of various signal and data analysis tools; one of them is illustrated in Fig. 6. Here, cavitation intensity is presented by the color, and the three black lines point to the three cavitation mechanisms found in this particular turbine.

In the multidimensional technique for turbine cavitation diagnostics and monitoring, a huge quantity of high-frequency data (up to 1 or 2 MHz from each sensor, acquired over at least 100 runner revolutions) acquired by means of a sufficiently high number of sensors distributed over a turbine is subjected to rather complex signal and data processing, which resolves all M×V×B processes, and combines this set of data into more compact final information. In the case of permanent monitoring, the resulting data are reduced to a scalar and vector format comparable to that used in vibration monitoring; these cavitation data are sent to the central unit of a plant monitoring system for logging, trending, and further analysis. An important specific issue here is logging the accumulated cavitation intensity. This may be used to assess the running state of cavitation-erosion development and to organize condition-based maintenance. The number and location of the sensors and the details of the monitoring algorithm are usually determined in an introductory diagnostic on-site cavitation test. Due to the fact that cavitation in every turbine has its particularities, the use of an off-the-shelf monitoring system is not recommended.
3. Results

The second phase of multidimensional data processing – a step-by-step synthesis – results in various descriptions of the cavitation dependence on turbine operation parameters (two water levels, distributor, and, for Kaplan turbines, runner opening, discharge, power):

- $M \times V \times B$ characteristics of the guide-vane/runner-blade pairs specifying, for each of the $M$ cavitation mechanisms, the components of the cavitation intensity on each of the $B$ runner blades as influenced by each of the $V$ guide vanes and by the position behind the spiral casing;

- $M \times B$ characteristics of the runner blades specifying the cavitation intensity on each blade averaged circumferentially, thus being a mean over all the guide vanes and all the positions behind the spiral casing;

- $M \times V$ cavitation characteristics of the guide vanes; these generally do not describe any cavitation on the vanes but specify the mean influence each vane has on the runner blade cavitation;

- $M$ and, finally, one global cavitation characteristic specifying the mean cavitation intensity in the turbine.

Fig. 7 – Erosion-rate estimate derived for Grand Coulee Dam Francis turbine G-20 by means of the multidimensional technique, compared to the efficiency curve.

Fig. 8 – Comparison of 6 nominally identical Francis turbines in Landsvirkjun’s Burfell HPP, Iceland, reveals differences in the cavitation-threshold height and in the intensity of the developed cavitation.
Fig. 9 – Guide-vane cavitation characteristics of the six Burfell turbines.

Fig. 10 – Cavitation in Kaplan unit 1 at Electricité de France’s Kembs HPP, France, with two versions of cam installed: the original cam designed in a model test and the optimized cam determined in an index test on the prototype; it is recommended to include cavitation in the index test.

Fig. 11 – Spatial distribution of cavitation intensity behind the spiral casing in Kembs unit 1; the intensity is normalized to the value in the direction denoted by the black dot.
The global characteristics are illustrated in Figs. 7 and 8, and the guide-vane characteristics in Fig. 9. These data can be used for turbine operation optimization (Fig. 7 – avoiding load ranges with high cavitation intensity) and plant operation optimization (Figs. 8 and 9 – loading less the units which cavitate more strongly, while keeping the needed total power production).

Various specialized forms of turbine cavitation characteristics are useful, e.g. those which check other turbine characteristics such as the cam in a Kaplan unit (Fig. 10) or which explicitly describe the spiral-casing influence (Fig. 11). The latter shows that, in the turbine tested, most cavitation appears in a rather narrow angular segment of the spiral. It also shows that between the two highest power values a steep rise of intensity starts; this points to a new cavitation mechanism. Cavitation characteristics like those in Figs. 10 and 11 reveal the possibilities of turbine improvement.

4. Comparison with simple techniques

Simple techniques for cavitation monitoring follow a straightforward logic applied in most other hydropower measurements: using a sensor suitable for the quantity to be assessed, and estimating the mean value or other suitable value of the sensed quantity. For cavitation, this is not optimal for two reasons:

- The results delivered by such cavitation monitors heavily depend on the sensor location (cf. the differences in the amplitudes of different curves in Fig. 3). Even if differences in the obtained mean values were compensated by calibration, differences in the forms of the peaky curves, which describe the interactions of different turbine parts, show that, for a selected sensor location, some cavitation components may be hidden and some others may be overestimated. Thus, readings of the one-sensor monitor may turn out not to be representative and may thus incorporate a high unknown bias error;

- Simple signal processing algorithms used in the simple monitors ignore information such as that contained in the patterns in Fig. 3. Thus, such monitors cannot deliver data on cavitation details. If they were used to do so on the only available pattern, the obtained information may be wrong.

In contrast to this, the multidimensional technique uses signals from sensors in many locations and processes them in an appropriately complex way. This makes the resulting data representative, the mean values of cavitation intensity estimates close to the true mean total intensity values, and the conclusions on the details of the cavitation processes available and correct.

![Image](image.png)

**Fig. 12** – Readings of the blade-passage-modulation-level obtained on 32 guide vanes (different colors – different vanes). The simple monitor yields as the result the bold black-line curve with dots.
Fig. 13 – Cavitation prediction made by means of the simple monitor using one sensor installed on the draft tube wall, compared to the multidimensional result (red – erosive operation, green – erosion-free operation, yellow – transition range).

In Figs. 12 and 13, the multidimensional technique is compared with the two simple monitors installed at Grand Coulee Dam\textsuperscript{2}, the monitor with one sensor on one guide-vane lever and the modulation amplitude as the output (Fig. 12), and the monitor using one sensor on the draft tube wall and the RMS signal value as the output (Fig. 13). Fig. 12 shows how poor and unpredictable the results can be when based on one sensor only. Depending on the sensor location, the power setting at which the assessment of cavitation intensity reaches its maximum varies by 50 MW or 100 MW. This illustrates the situation with both one-sensor monitors. The second simple monitor has one more problem: relying on a sensor in a location in which non-erosive free-vortex cavitation prevails and interpreting the two-year readings\textsuperscript{3} in the wrong way yielded a paradoxical result (Fig. 13).

A comparison of the two classes of cavitation monitors is recapitulated in the following table.

<table>
<thead>
<tr>
<th></th>
<th>Simple</th>
<th>Multidimensional</th>
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<tbody>
<tr>
<td>Number of sensors in a good diagnostic test</td>
<td>1</td>
<td>1 for each guide-vane</td>
</tr>
<tr>
<td>Number of sensors in permanent monitoring</td>
<td>1</td>
<td>typically 6</td>
</tr>
<tr>
<td>Signal and data processing algorithm</td>
<td>simple</td>
<td>complex</td>
</tr>
<tr>
<td>Delivers mean erosion rate estimate</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Delivers accumulated erosion estimate</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Represents all locations in a turbine</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Recognizes different cavitation types</td>
<td>negligible</td>
<td>yes</td>
</tr>
<tr>
<td>Delivers diagnostic details (runner blade quality, etc.)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Relative sensitivity in detecting deterioration effects</td>
<td>~1</td>
<td>~80</td>
</tr>
<tr>
<td>Overall accuracy and reliability of results</td>
<td>low</td>
<td>high</td>
</tr>
</tbody>
</table>

The high ratio of the monitoring sensitivities is a consequence of the fact that a vibro-acoustical signature of the initial deteriorating effect is compared to the total cavitation signature in the simple monitor and to the signature stemming from a spatial resolution cell in the multidimensional monitor.

6. Review and conclusion

The multidimensional technique for cavitation diagnostic tests and monitoring uses sensors distributed over a turbine and conducts complex signal and data processing. It yields reliable estimates of cavitation intensity and delivers diagnostic details on cavitation. This can be used to optimize turbine or plant operation for minimum erosion, organize predictive maintenance related to cavitation, and identify turbine parts which could be improved.

Simple cavitation monitoring techniques, based on one sensor and simple signal processing, may deliver intensity estimates with a high bias error. They ignore most of the information on cavitation contained in vibro-acoustic signals and do not yield details of cavitation.

The Author

Dr. Branko Bajic is managing director of Korto Cavitation Services. He has great experience in cavitation diagnostics and monitoring and is the creator of several innovations in the field.

Appendix 1 – Typical installation of the multidimensional monitoring system

The cavitation sensors are installed on the guide-vane shafts or levers, in robust protection boxes.

Data sources:
- (Typically) 6 cavitation sensors
- Key phasor
- Sources of operation data (head and tail water level, distributor opening, runner opening for Kaplan units, flow through a turbine, turbine power setting).

The samples of random cavitation signals, representative in space and time, are fed to the cavitation processor which implements the multidimensional monitoring algorithm in order to reduce a high volume of high-frequency data to limited-size data on deterministic cavitation signatures. Usually, total cavitation intensity is delivered as an analog signal, and these data and the data on the details of cavitation are published on LAN.

The system can be used independently or as a cavitation channel of a general plant monitoring system.
Appendix 2 – Multidimensional Cavitation Tests on Turbines – How are they done?

The technique is non-destructive. We glue or fix with magnets the basic cavitation sensors A on the shaft or lever of each guide vane. These sensors cover the frequency range from the turbine revolution frequency up to 0.3 MHz. We also use several other types of cavitation sensors B installed in other locations and covering higher frequencies. By means of the key phasor C, we synchronize the signal acquisition and processing with the turbine rotation. We acquire operation parameters by means of D (head and tail water level, distributor opening, runner opening for Kaplan turbines, flow through the turbine, and the turbine power setting). Through E/F/G/H, we feed the signals to the cavitation processor I. The processed data and, where necessary, the raw data, are saved in the high-capacity disks J. The test is controlled through the supervisory computer K, and the computers L which are used to communicate with the plant operators.

The preparation of the test at the plant lasts 1-3 days. A still stand lasting half an hour or one night is needed, depending on the machinery details. The rest of the preparation is done under normal operation.

The turbine is tested on 20-30 power settings; local control is recommended. For one water-level combination, the measurement lasts 2-3 hours.

The data analysis, based on software implementing Korto’s multidimensional algorithm, is often recursive and takes 2-6 weeks. The result is detailed turbine cavitation characteristics.

APPLICATION

# Operation optimisation for minimal erosion
# Improvement of turbine cavitation performance
# Predictive maintenance (in the case of stable water levels, the test is sufficient; otherwise, permanent monitoring is necessary).