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More on multidimensional cavitation monitoring

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Introduction

In a paper presented at Hydro 2002 [1], an innovative multidimensional approach to monitoring cavitation and other dynamic processes in hydro power units was proposed. The approach is based on:

- intensive sampling of observable data on relevant dynamic processes, in space, time, instantaneous position of the runner, and the domain of state variables;
- truly multidimensional analysis of the interrelations between these data;
- incorporation of empirically and theoretically developed models of the monitored processes in the monitoring algorithms;
- derivation of sophisticated characteristics that combine two or more primary quantities into a directly interpretable and reliable description of machinery health.
- A number of examples presented in [1-4] show that the approach is efficient both as a diagnostic tool and as a means for a highly sensitive detection of changes in machinery operation and deteriorating effects.

The multidimensional concept was initially introduced to diagnose and monitor cavitation [5]. First, turbines with a high number of runner blades were considered. The concept was later broadened to include the case of a low number of runner blades as well [6]. The approach was based on a detailed study of sensors and signal and data processing problems [7]. The advantages of the multidimensional monitoring system as compared to simpler ones is that it delivers as detailed a description of cavitation as imaginable and thus enables:

- recognition of different cavitation mechanisms (different types of cavitation or the same type appearing in different locations);
- assessment of the role played by turbine parts in cavitation;
- estimation of the spatial distribution of cavitation in the turbine; and
- achievement of extremely high sensitivity in detecting changes in turbine cavitation performance and the onset of detrimental effects.

The full performance of a multidimensional monitor can be achieved only if it is designed to fit each individual situation, i.e. if it is conceived based on the results of an introductory diagnostic test. This guarantees the inclusion of all facets of the monitored processes and makes the reduction of the monitoring system possible. As a result, a highly efficient, rather simple system can be obtained. This simplifies the maintenance of the system and reduces initial and later costs. Nevertheless, if the multidimensional monitoring is applied, such a simple system can yield better performance than a costly, complicated system based on a different approach.

In the accompanying paper [8], an illustration of such a simple monitoring system and the results of its application are given. The implementation presented here includes cavitation in the list of the monitored quantities and uses the same hardware for processing it and other quantities. In this paper, an alternative is presented: here, an example of the independent cavitation monitor is illustrated. Also, typical results, as delivered by a multidimensional monitor are shown. Such results can be achieved by a cavitation monitor of any implementation, provided it is based on the multidimensional algorithm.

Turbine cavitation characteristics

The multidimensional cavitation characteristics of a turbine [5], which are included in the monitoring algorithm of the cavitation monitor and used in the diagnostic tests, are defined in the following table.

Name	***Independent variables***	***Meaning***	***Definition***
Detailed cavitation characteristic	Runner blade number, *b* Guide vane number, *v* Operation parameters, *P*	Intensity of the component of cavitation on *b* which is influenced by *v*, as developed while the turbine is being operated in *P*	Raw input data
Runner cavitation characteristic	Runner blade number, *b* Operation parameters, *P*	Intensity of the cavitation on *b* as developed while the turbine is being operated in *P*	Intensity of the detailed characteristic summed over all *v*'s
Wicket-gate cavitation characteristic	Guide vane number, *v* Operation parameters, *P*	Intensity of the component of the cavitation which is influenced by *v*, as developed while the turbine is being operated in *P*	Intensity of the detailed characteristic summed over all *b*'s
Global cavitation characteristic	Operation parameters, *P*	Total cavitation intensity in the turbine while it is being operated in *P*	Intensity of the detailed characteristic summed over all *b*'s and all *v*'s

Here *P* stands for a set of relevant operation parameters such as power setting, head and suction head.

With respect to cavitation mechanisms, each of these characteristics can be defined for: the total cavitation in the turbine, each cavitation mechanism separately, or the erosive mechanism or the group of erosive mechanisms.

The calibration of the characteristics can be: relative, with an arbitrary reference, or absolute, in kilograms of the metal mass lost in a specified time interval (e.g. 10000 hours) while the turbine is being operated in *P*.

An example

The characteristics defined above, as obtained by detailed cavitation monitoring, are illustrated by the example of two 48 MW vertical Francis turbines in a plant operated at an almost constant head and rather constant tail water level. The turbines differ slightly in the runners; all other parts are the same. They have 20 guide vanes (*v* above) and 17 runner blades (*b* above).

The characteristics found are shown in Figs. 1-9. Turbine A is considered in all the figures. In Figs. 4 and 6, turbine A is compared to turbine B. The set of the operation parameters *P* is reduced to the power. While commenting the figures, brief notes on application possibilities are made.

Four cavitation mechanisms are identified in the two turbines - areal cavitation on the suction side of the runner blades; leading edge cavitation; areal cavitation which disappears in free water downstream from the blade; and cavitation in the free vortices in the draft tube. Only the first mechanism is erosive. The characteristics in Figs. 1-3 incorporate all three mechanisms related to the runner blades. Fig. 4 shows the total intensity of cavitation close to the runner blades and the erosive mechanism separately, while in each of Figs. 5-9, different single mechanisms are shown.

Both ways of calibrating the cavitation characteristics noted above are used in the figures. In Figs. 1-4 and 6-9 the relative intensity normalised to the maximal intensity of the erosive mechanism is given in percentages, and in Fig. 5 the absolute calibration yielding metal loss is used. Here kilograms of electrodes used in a repair are shown instead of showing the loss of the runner body itself. As to the characteristics describing the turbine parts, they, of course, show the percentage by which a considered part contributes to the total effect. It is important to note that the wicket-gate characteristic does not describe cavitation on the guide vanes but, instead, specifies a portion of the intensity of cavitation on the runner blades which senses the influence of a guide vane.

Fig. 1 - ***Detailed cavitation characteristic*** consists, in the case being considered, of 20 graphs like this, one for each guide vane. The characteristic describes both the cavitation quality of a runner blade and the severity of the flow distortion caused by a guide vane. This is the most detailed description of the turbine's cavitation behaviour. It can be used to make a diagnosis of the cavitation and to decide if an improvement is necessary and possible. In this particular case, the turbine parts' quality is rather uniform.

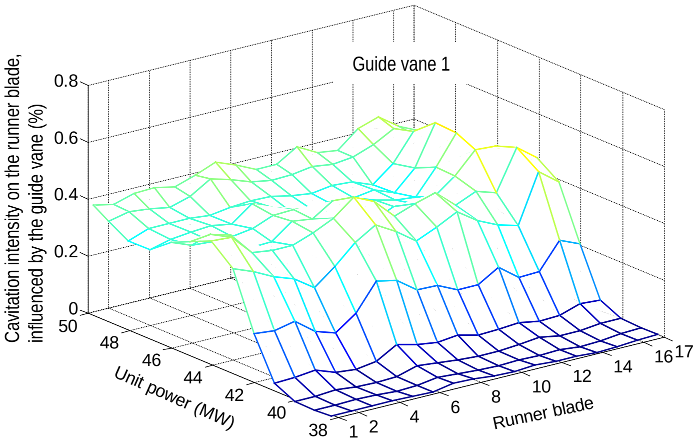


Fig. 2 - ***Runner cavitation characteristic*** assesses the average cavitation quality of each runner blade, i.e. its quality averaged over all the wicket vanes. In this case, there are no large differences among the blades.

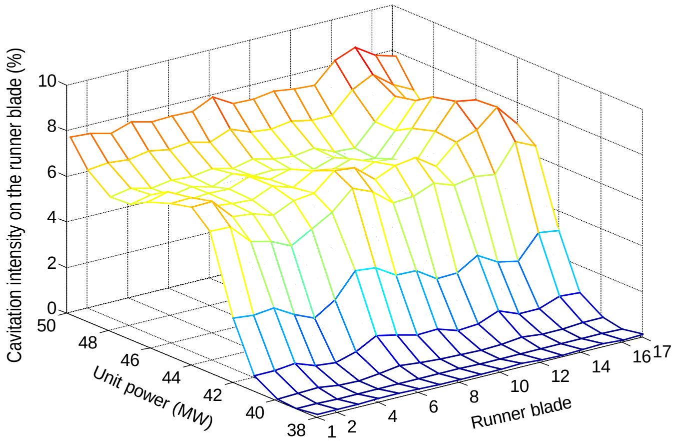


Fig. 3 - ***Wicket-gate cavitation characteristic*** reflects both differences in wake-fields behind individual vanes, i.e. their cavitation-related quality, and the differences in the flow conditions behind different parts of the spiral casing. Here, the second effect is dominant.

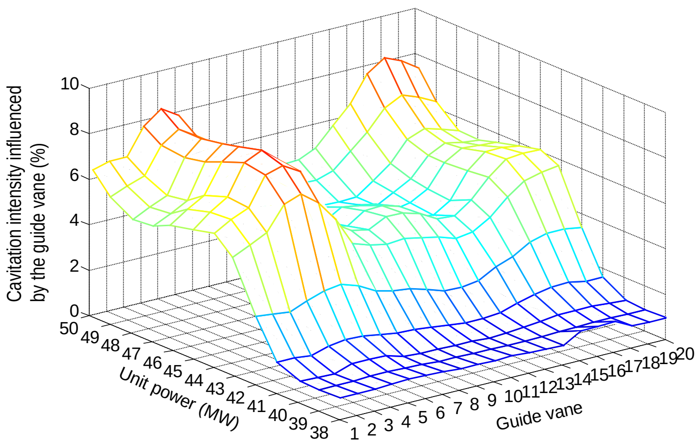


Fig. 4 - ***Global cavitation characteristic*** yields the simplest description of cavitation in a turbine. By comparing all units in one plant in respect to the differences as found here (the cavitation intensity on Unit B is 25 % lower than on Unit A, and the cavitation starts at 1 MW higher loading), an operation plan can be made to minimise the total erosion. Usually, the characteristics vary more than these two, which makes such optimisation even more efficient.

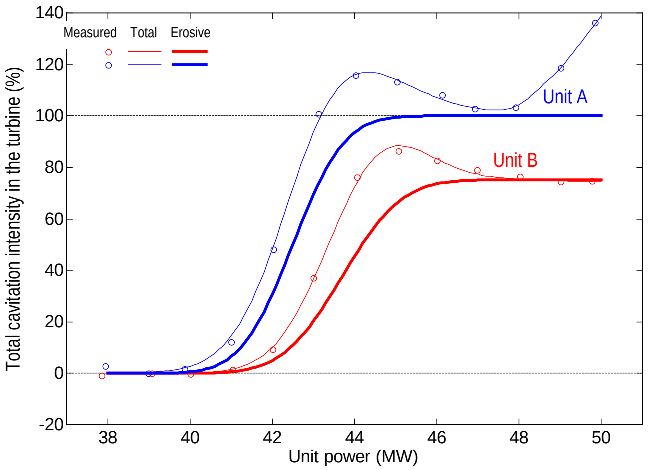


Fig. 5 - ***Absolutely calibrated global cavitation characteristic*** yields erosion rate for different operation conditions. By combining this vibro-acoustic data (accompanied by the uncertainty bounds) with the planned loading statistics for a future period, the accumulated erosion in that period can be predicted. This enables optimisation of the maintenance schedule.

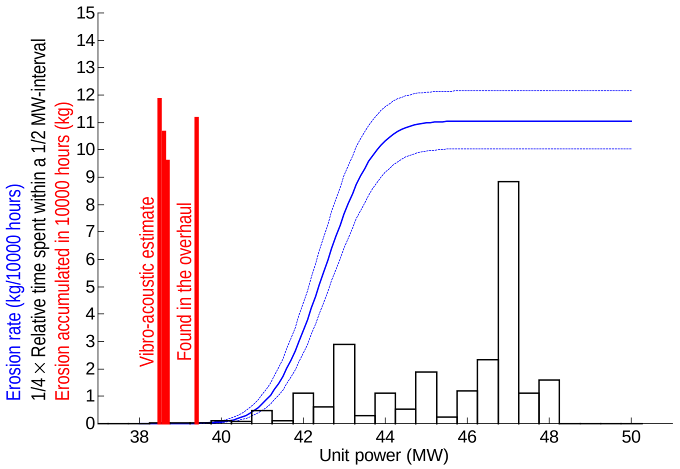


Fig. 6 - This ***special form of the global cavitation characteristic*** yielding cavitation intensity in the draft tube shows that the Unit B, which has lower intensity of the erosive cavitation (Fig. 4), has stronger cavitation below the runner, in the draft tube. This shows that the stability in the partial-load operation of Unit B must be checked.

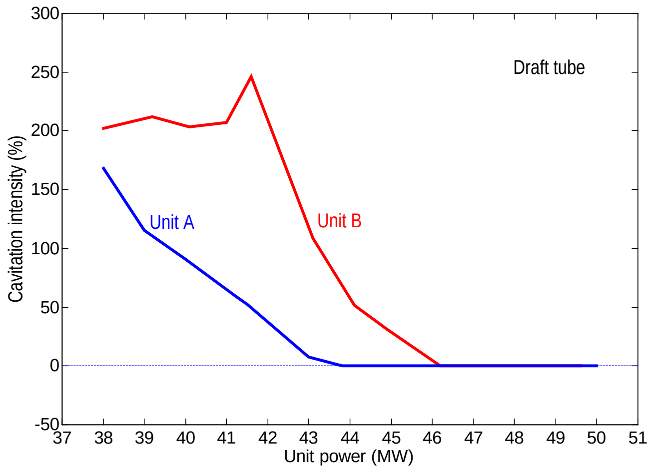


Fig. 7 - Well-interpreted rich data on cavitation delivered by the multidimensional monitoring enables ***recognition of the cavitation mechanisms*** and their quantitative assessment. In the group of this and two subsequent graphs the result of such a procedure is presented. The basic format, as in Fig. 3, is used to present three components of the total intensity, which stem from three cavitation mechanisms related to the runner. In this figure, the erosive areal cavitation is quantified.

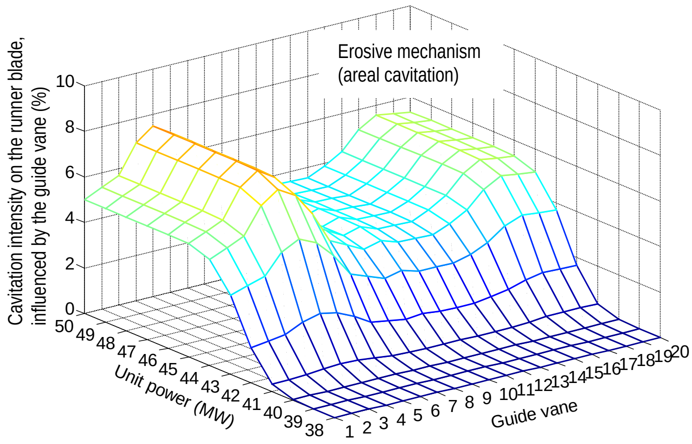


Fig. 8 - Leading edge cavitation causing no erosion in this particular case.

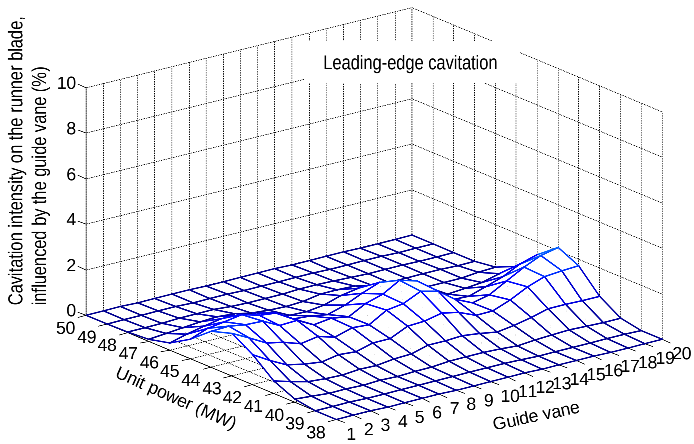
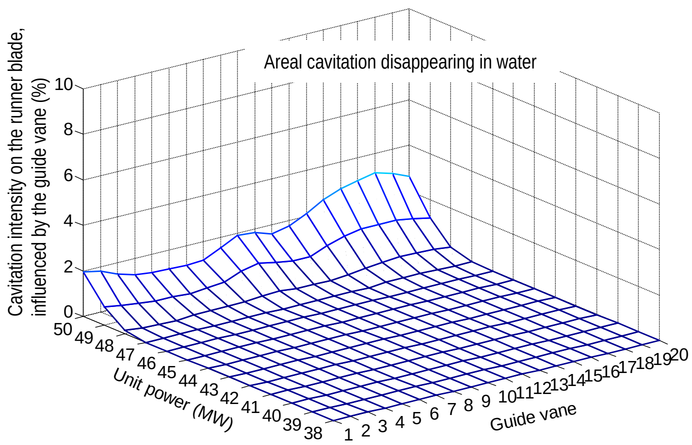


Fig. 9 - A component of the areal cavitation intensified at highest loading degrees. The cavities that are born upstream, on the blade, develop to such a degree that they survive till they fall into the recovered high-pressure region behind the trailing edge. This cavitation is rather intense but causes no harm to the blades. If improvements of runner blade profiles are necessary, such descriptions of the cavitation mechanisms can show the way. Due to unfavourable geometry, not all the mechanisms can be observed in model tests. However, they are detected and assessed in the in-plant multidimensional monitoring.



Displaying data

There are many ways to present the results that a multidimensional cavitation monitor delivers. One of them is shown in Fig. 10.

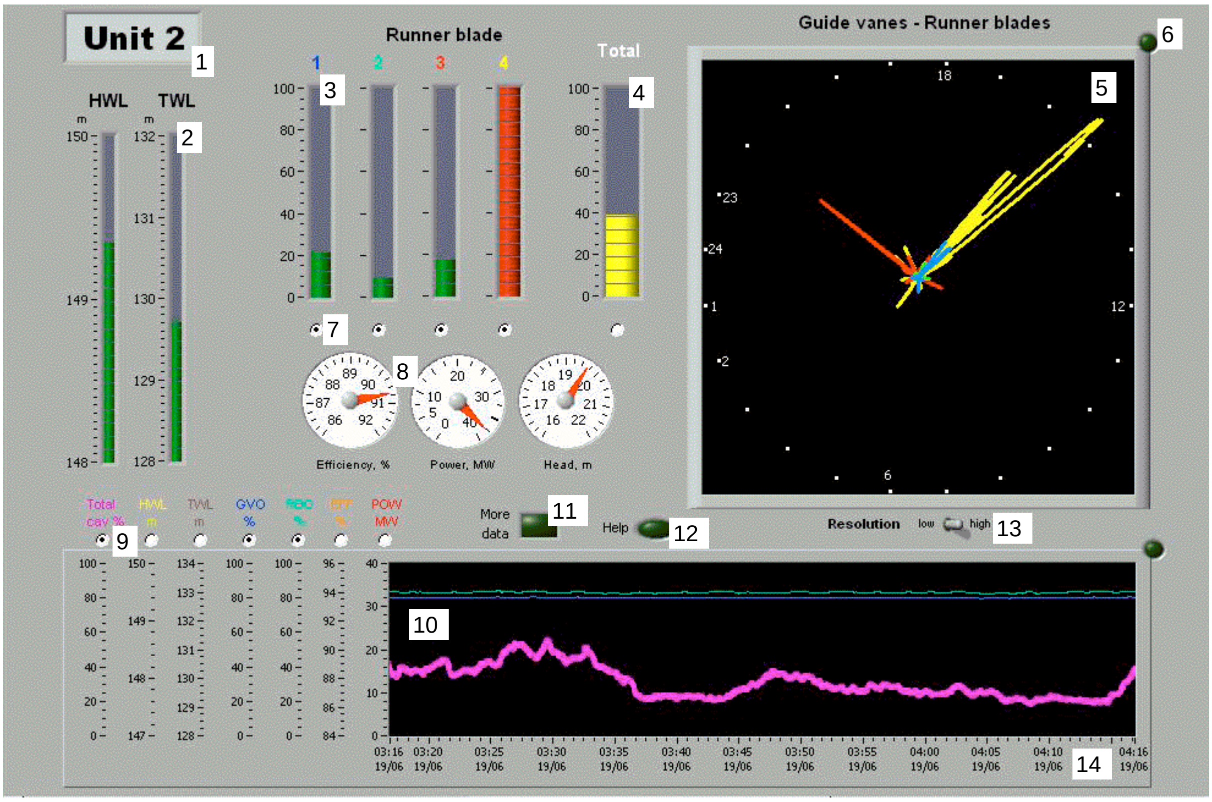


Fig. 10 - One monitoring system can serve one or more turbines. The results for different turbines can be displayed independently or on a common display. Here, the former is adopted (1). Relevant operation data, such as head and tail water levels (2), and efficiency and power data (8) are presented in addition to the data on cavitation. Cavitation intensity is presented for each of the runner blades (3) - four of them in the example shown - and for the entire turbine (4). For each of the blades, the circumferential distribution of intensity over the guide vanes (5) is shown; this can be made in two different resolution grades (13). Behind the outputs shown, there are multidimensional algorithms implementing the cavitation characteristics discussed above: (3) - runner characteristic, (4) - global characteristic, (5) - detailed and wicket-gate characteristics. The numerical results can be followed in a log (10), the content (9) and the length (14) of which can be varied. Also, the content of the polar display (5) can be selected (7). Both the polar diagram and the log can be enlarged (6). The command (11) opens further options of the display. Among others, these incorporate accumulated erosion, the display of cavitation intensities over the operation parameters and over the shell diagram. The operators need not know much in advance: simple on-line help is available (12). Behind all this, there is an Intranet connection to the general monitoring system of the plant, the PC's of the plant staff, and other plants in the chain, if applicable. All data are delivered to the control system and so are the alarms. There, they can be used for operation optimisation.

Implementation

Characteristic for the multidimensional monitor is the application of a rather high number of sensors; 4, 6 or 8 per turbine is a typical number (Fig. 11). Acoustic emission sensors and high-frequency accelerometers are used in cavitation monitoring systems, and, in addition, fast pressure transducers and hydrophones are used in diagnostic tests. The sensors are mounted to pick up cavitation noise in the water itself, or to sense structure-born sound generated by cavitation in turbine metal parts. Usually, all approachable locations around the runner are covered with sensors (Fig. 12). A special spectrum normalisation technique [9] is used to broaden the operation frequency range of the sensors far above their nominal limit frequency (Fig. 13). Special in-situ calibration is

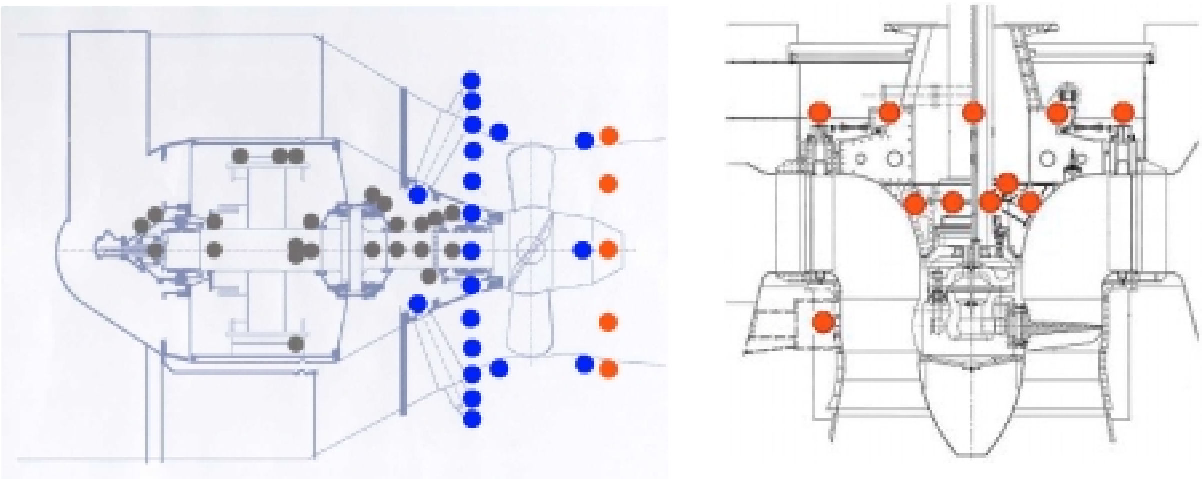


Fig. 11 - Examples of sensory systems. A large number of sensors is used in a cavitation diagnostic test (blue and red dots). Only a part of them is used for permanent monitoring of cavitation (red dots). The other dots at the bulb unit denote various other sensors used in a general monitoring system.

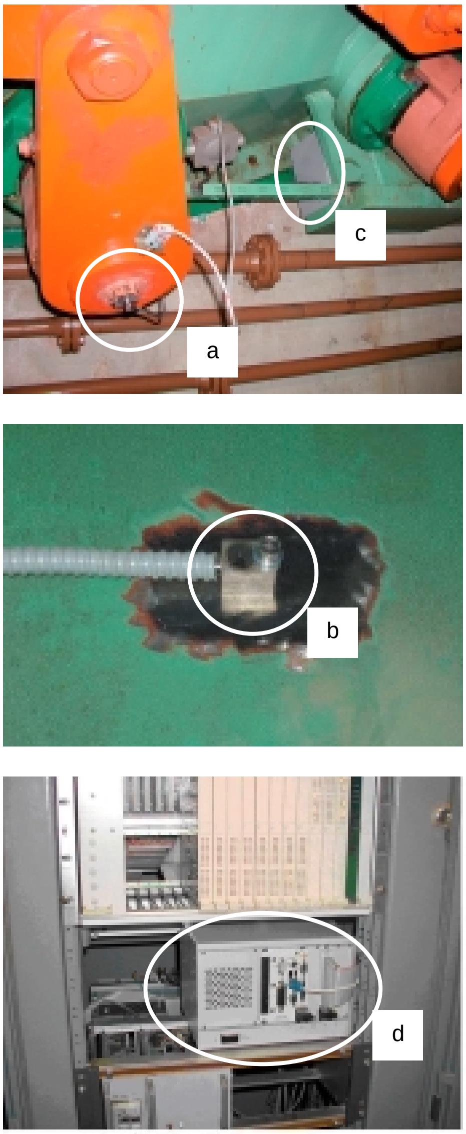


Fig. 12 - For permanent cavitation monitoring, only sensors in the air are used. They are mounted in a simple way

(a) on a guide-vane stem, or

(b) on the head cover, the draft tube wall, the man-hole wall, or the lower guide bearing.

The rest of the hardware of a multidimensional cavitation monitoring system consists of

(c) the accompanying signal conditioning electronics, the signal cables, and

(d) the cavitation processor, which is a suitable industrial computer with a suitable high-frequency analog-to digital conversion card.

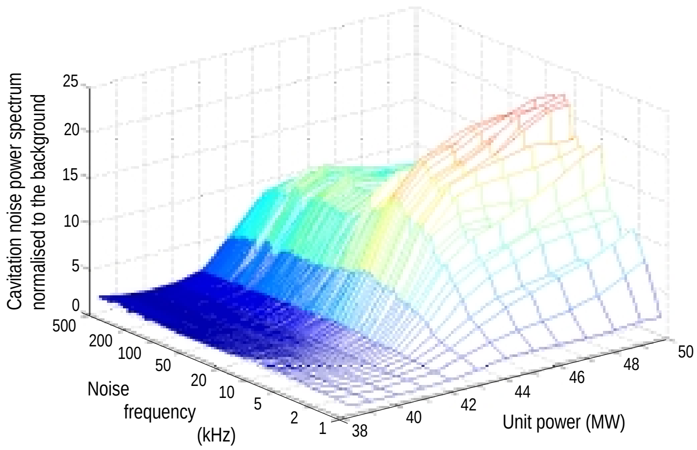
If output data on cavitation is delivered to a general plant monitoring system or, via Intranet, to PC's of the plant staff, the cavitation processor is a passive unit which can be installed almost anywhere. Such a case is shown as d.

The cavitation monitoring system needs a synchronisation signal and some data on the operation. These may be taken from the unit control system.

performed, which equalises the responses of the sensors working in such a high-frequency range. It also compensates for the differences in mounting details.

The cavitation processor copes with a large quantity of high-frequency data and reduces that into a rather small set of scalar and vector data like the ones presented in Fig. 10. Thus, typically, much more is required from the cavitation processor than from those used for processing other signals in a general monitor. If the cavitation monitoring system is a part of a general plant monitoring system, there are thus two options: the computer used for the cavitation processor processes all the signals, or - if a separate computer is used for other quantities - another dedicated computer is used as the cavitation processor.

Fig. 13 - In order to extract all useful information from the signals from the sensors and to derive unbiased estimates of cavitation intensity, the entire band width of cavitation radiation has to be acquired and processed. As shown in this signal-to-noise ratio diagram, describing the typical cavitation sensory configuration, energy in the kiloherz range can be neglected but noise frequency as high as 1 MHz should be included into the processing.



To conclude, the multidimensional cavitation monitoring system can be designed:

(a) as a stand-alone unit incorporating the operator interface,

(b) as a passive, separate system that reduces cavitation signals to data on cavitation and delivers these to the general plant monitoring system; or

(c) as an integrated monitoring system that monitors all the quantities needed, including cavitation; this is the variant described in the accompanying paper [8].

The operator interface does not depend on the implementation variant. On users' screens - either the screen on the monitor itself or those in users' PC's - the cavitation data can be presented either

(i) independently, in a manner illustrated in Fig. 10; or

(ii) incorporated into the set of all monitored data, in the way shown in [8].

Simple vs. Multidimensional cavitation monitor

Information content

- S Only delivers data equivalent to that from the global cavitation characteristic, i.e. total cavitation intensity (as shown in Fig. 4 or 5), and some other signal signatures as modulation depth etc. as well.
- M Delivers this data and also data equivalent to that contained in the set of other turbine cavitation characteristics. This yields diagnostic data on turbine parts (Figs.1-3) and cavitation mechanisms (Figs. 7-9).

Bias error

- S By using only one or a few sensors, the simple monitor does not cover the entire volume in a turbine and thus may have a high bias error in intensity estimates (its data as in Figs. 4 and 5 may be erroneous).
- M Correctly covers the entire turbine volume and all the turbine parts and thus yields unbiased, representative estimates of all cavitation components.

Monitoring sensitivity

- S Detects the onset of a detrimental effect by looking for a change in the total cavitation intensity.
- M In early phases of development, the detrimental effects are usually well localised. Thus, the multidimensional monitor, which resolves turbine parts and parts of the turbine volume, detects them by looking for a change in the cavitation intensity in a resolution cell. This makes the sensitivity of the multidimensional monitor compared to the one of the simple monitor higher by a factor equal to the number of runner blades, the number of guide vanes, or the product of these two numbers, depending on which of the cavitation characteristics is included in the monitoring algorithm.

Installation

- S Mostly, adjustment of few amplifications suffice for a simple monitor to be ready for use.
- M An introductory diagnostic test is needed in order to design the monitor for a given turbine. However, the test delivers detailed turbine cavitation characteristics, reveals turbine's weak points and, if necessary, shows what improvement steps can be made.

Costs

S A minimum preparatory work in the plant, a minimum investment in the sensors.

M More for the work in the plant, more for the sensors. However, quick payback through improved turbine maintenance is ensured as is much safer operation.

Monitoring vs. model tests

- There are strong scale effects in cavitation modelling [10]. Thus, it is recommendable to control cavitation on the prototype, in the acceptance test.
- Turbine cavitation performance varies in time, which makes continuous control necessary.
- In a typical model cavitation test, much less useful data for practical operation of the prototype is obtained than by means of the in-plant multidimensional vibro-acoustic test (Fig. 14).
- In some cases, not all types of cavitation can be seen in a model test. All can be heard and assessed in a good, multi-dimensional in-plant vibro-acoustic test.

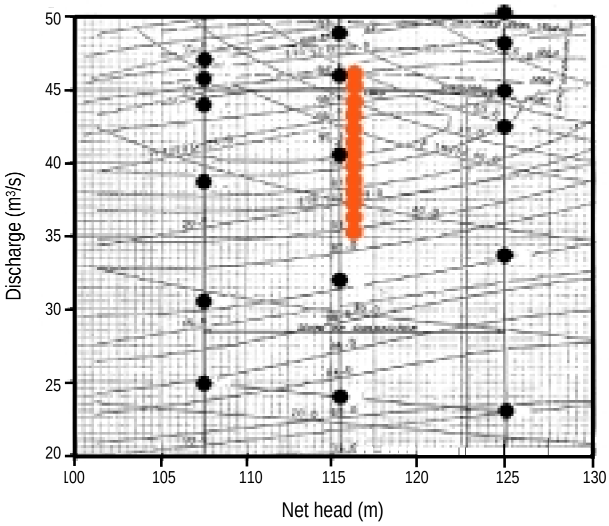


Fig. 14 - Log of the model tests of the turbines presented in Figs. 1-9: the black dots stand for model tests and the red dots for the multidimensional monitoring results. The latter cover the whole range of a normal operation. Thus, only two model points are directly useful in practice.

Conclusion

The multidimensional cavitation monitor delivers detailed diagnostic data and reliable estimates of cavitation intensity. It has a very high sensitivity of detection of detrimental effects.

An introductory diagnostic test is needed in order to design the multidimensional cavitation monitor for a given turbine.

The cavitation monitor can be implemented as a stand-alone unit, a passive system connected to the general plant monitor, or integrated into the general monitor.

A simple, less expensive implementation of both the cavitation and the general monitor is possible without a loss in performance.

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