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Multidimensional monitors for hydroelectric power plants

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Introduction

Significant savings in maintenance costs and improvement of profitability and reliability of hydropower unit operation can be realised if operation and maintenance are optimised based on actual characteristics of a turbine, generator and other major part of the machinery. A necessary insight into these characteristics can be obtained through a combination of

- detailed introductory and less detailed periodic **diagnostic tests**, and
- permanent **monitoring** of the essential processes in the machinery.

Optimal results are obtained by means of a **plant-specific monitoring system**, the performance of which is matched to the unit's individual characteristics as determined in the introductory diagnostic test.

There are several ways to perform diagnostic tests and to design a monitor. Korto Cavitation Services have developed and use the **multidimensional method** that consists of:

- intensive sampling of observable data on relevant dynamic processes, in space (Fig. 1), time, and the domain of state variables;
- truly multidimensional analysis of the interrelations between these data;
- construction of empirical and theoretical models of the processes, and their application in the analysis;
- derivation of sophisticated characteristics that combine two or more primary quantities (vibration levels, pressures, temperatures, etc.) into a directly interpretable and more reliable description of the machinery health; examples: total cavitation intensity that incorporates unbiased estimates of cavitation in all locations within a turbine, spider-to-shaft joint stability, amplitude and direction of the force caused by rotor eccentricity, etc. (Fig. 2).

The ability of the multidimensional monitors to make representative assessments by suppressing sources of bias errors, and to extract specific data needed for assessments of relevant machinery health signature while suppressing disturbances and spurious responses of the measurement system and machine structure, results in:

- reliable basis for operation optimisation,
- very high sensitivity in detecting deterioration effects in early phases of development,
- rich and reliable data on the causes of changes that facilitate reliable diagnostics and optimisation of the repair schedule.

The performance and typical output data formats of the multidimensional tests and monitoring are illustrated in the following paragraphs by the case of cavitation in bulb unit A of the **HPP Dubrava**, Croatia (Fig. 1, right: head 18 m, flow 250 m^3/s, power 40 MW, rotational speed 125 min^{-1}, number of guide vanes 24, number of runner blades 4).

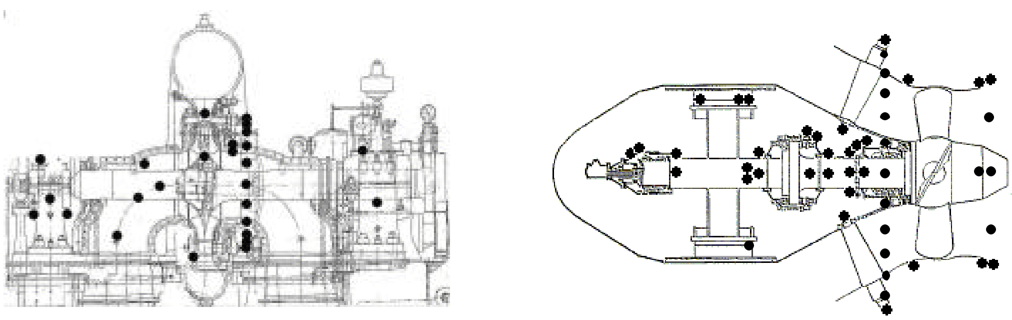

Fig. 1 - In a multidimensional diagnostic test, in which one aims at deriving detailed characteristics of the machinery, establishing the reference for future checks, and reliably assessing the machinery health, a high number of various sensors mounted at different locations is used: examples from the tests on an old Francis unit (HPP Walchensee, Germany) and on a modern bulb unit (HPP Dubrava, Croatia). For permanent monitoring, the number of sensors is reduced but is, especially for cavitation, still higher than commonly practised.

The example shows how detailed data not obtainable by simpler techniques can be derived: identification of different cavitation mechanisms that might be occurring in a turbine (different cavitation types or the same type at different locations), assessment of cavitation quality of turbine components. The multidimensional vibro-acoustic technique for cavitation testing and monitoring was introduced in [1] and presented in practical terms in [2]; the multidimensional approach to the analysis of other dynamic processes in hydropower units is illustrated in [3] and [4].

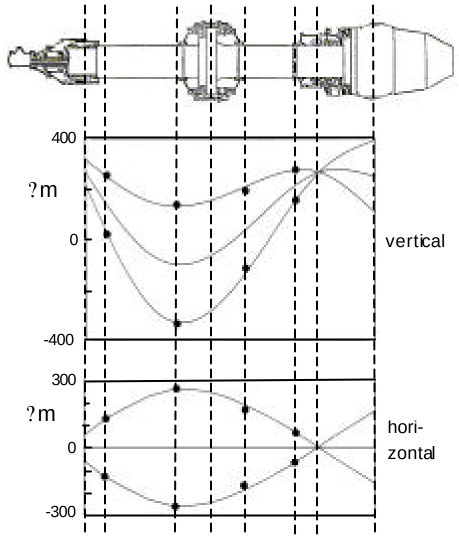

Fig. 2 - An example of the derived quantities resulting from the multidimensional approach: the data from four pairs of sensors sampling relative shaft displacement in four planes along the axis are combined, by means of an elastic beam model, into a compressed description of the shaft kinematics and dynamics [3]. Advantages: realistic and reliable estimates of conditions within the bearings, reliable estimation of the shaft coupling health, reduction of the quantity of data to be checked, and lower false alarm rate.

1. Simplest cavitation monitoring

Cavitation behaviour of the Dubrava unit A at a high power setting is illustrated in Fig. 3. The radial co-ordinate in little graphs stands for cavitation intensity, and the angle co-ordinate shows the instantaneous angular position of the runner. The peaks indicate the variability of cavitation within one revolution, which stems from the circumferential variations in the velocity field of the inflow to the runner. These variations are caused by the flow disturbances induced by the guide and stay vanes. The inflow variations and differences in guide vanes' quality with respect to cavitation also cause differences in the mean cavitation intensity in various locations around the runner. As is seen in the three denoted graphs, the differences in both the mean intensity (compare 1 and 2) and the form of the curves (1 and 3) are high.

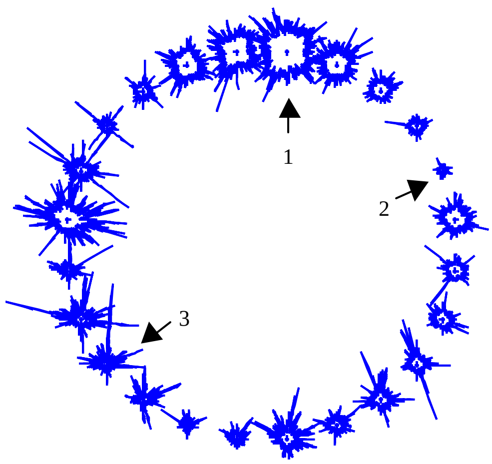

Fig. 3 - Polar presentation of the cavitation intensity dependence on the instantaneous angular position of the runner, as sensed in 24 locations around the runner

Implications for a cavitation monitor are obvious: should only one or too few sensors be used to sample cavitation spatially,

- cavitation intensity might be strongly underestimated or overestimated,
- data on the peaky structure of the curves (which, when deciphered, yield data on the role guide vanes play in the cavitation process) would not be representative and thus would yield false diagnostic conclusions, and
- even if details on guide vanes etc. are not required, the arbitrariness of the recorded data structure shows that not all types and locations of cavitation would be properly taken into account.

The conclusion is straightforward: even in a case of the simplest cavitation monitor which is, as in Fig. 4, expected to assess cavitation in a given operation condition by one numeric value only, one should sample cavitation by a sufficiently high number of spatially distributed sensors. The simple final result should then be derived from all the sensors combined into a synthetic spatially distributed one. This is how cavitation intensity values presented in Figs. 4 and 5 were obtained.

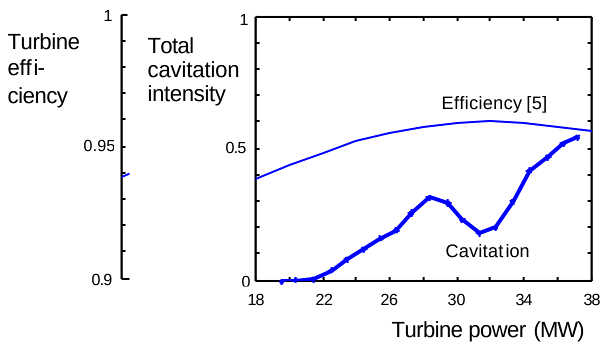

Fig. 4 - Basic turbine cavitation characteristics: the entire turbine - one numeric quantity

Once made representative, such simple cavitation estimates may be rather useful. Indeed, the non-monotonous cavitation curve in Fig.4 can be used to optimise the operation with respect to cavitation, and the data on operating conditions in Fig. 5 can be used to explain the causes of cavitation.

In the case presented, cavitation intensity is described by a formally normalised quantity. Full calibration of the erosion rate expressed in kilograms of metal lost per year is possible [6]. In addition to vibro-acoustic data, turbine power statistics and data on earlier cavitation damage repairs are needed here. The cavitation intensity thresholds like the ones drawn in Fig. 5 are defined in a similar way.

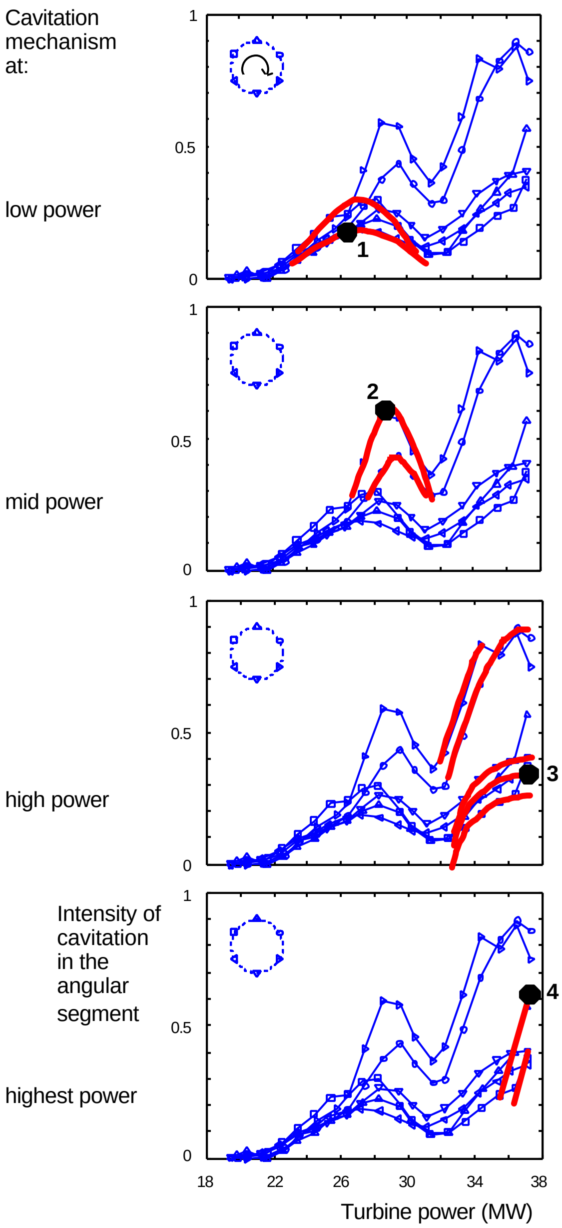

Fig. 6 – Decomposition of the cavitation curve in Fig. 4 into contributions from six angular segments in the turbine, presented here by six symbols, reveals the existence of four cavitation mechanisms in the turbine; these are represented by the thick lines.

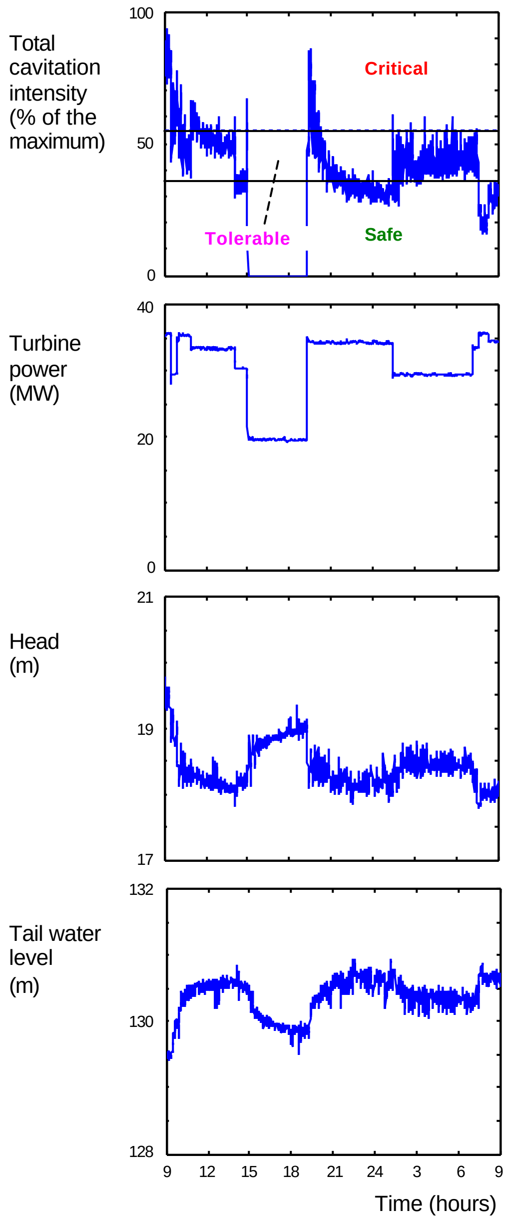

Fig. 5 - One-day log of a simple cavitation monitor based on a synthetic sensor

2. Further analysis: Cavitation mechanisms

The multidimensional analysis makes it possible to reveal the spatial distribution of cavitation within a turbine which often yields further insight into cavitation process. An example is shown in Fig. 6. While the total cavitation curve in Fig. 4 only shows that the process might have a complex structure, the curves with spatial resolution in Fig. 6, accompanied by further pieces of information like the ones illustrated in Figs. 7 and 8, enable its decomposition into contributions from different cavitation mechanisms. It is worthwhile noting that the highest-power mechanism would stay unnoticed without the spatially resolved data.

If a general insight into cavitation in bulb turbines is combined with the presented diagnostic data and other results of the multidimensional analysis, as well as the model test results [7], the conclusions regarding the cavitation behaviour of the Dubrava unit A are as follows:

At a typical head value, the cavitation threshold (within the usual operating range, 18-38 MW) lies at the power setting as low as 22 MW (see Figs. 4 and 6). At a low loading, there is hub cavitation (low power mechanism). Only weak cavitation or almost no cavitation appears at the turbine efficiency optimum. This cavitation optimum is rather narrow. Below and above it, inlet edge cavitation on the suction side of the runner blades combined with the tip clearance cavitation appears (the mechanisms at mid and high powers). Finally, the highest-power mechanism causes fully developed sheet cavitation on the suction side.

The differences in cavitation intensities in various angular positions within the turbine (cf. the two especially high curves in Fig. 6) stem from the low pressure region in the top locations. The runner rotates in clockwise direction, and the cavitation extremes generate strong noise and erosion at the locations in which cavities disappear, i.e. in the regions that are shifted from the vertical position in clockwise direction.

3. Identification of the role of turbine components

The multidimensional analysis of data (that are suitably measured, pre-processed in time and frequency domains, and reduced to the deterministic descriptions of intrinsically random raw input) incorporating influence of turbine loading, instantaneous angular position of the runner, and spatial position of the sensor, enables decomposition of cavitation intensity into components related to particular guide vanes and runner blades (Fig. 9). By performing such a decomposition, and by synthesising the resulting quantities into required combinations, one obtains directly interpretable final data in various useful formats [1, 2]. These describe the total cavitation intensity or intensity of a single cavitation mechanism, and present these quantities in total, or in the form of components related to runner blades and guide vanes or their pairs. Further, the data can be expressed with a chosen degree of spatial resolution or without it. One of such final formats is illustrated in Fig. 10.

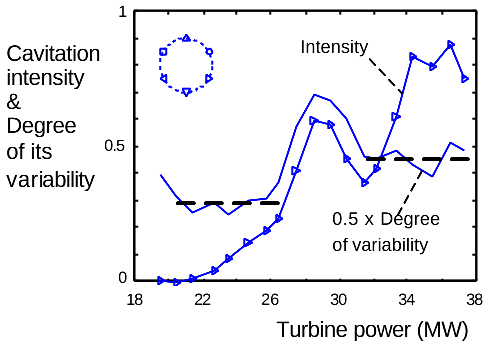

Fig. 7 - Cavitation variability, found within the power ranges in which different mechanisms act, helps in recognising the mechanisms.

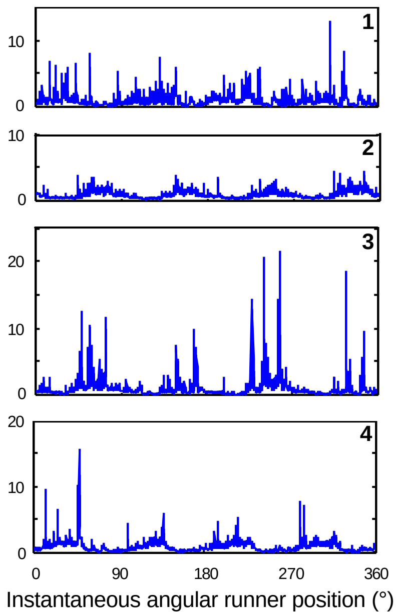

Fig. 8 - The curves of Fig. 3 in another format, normalised to the mean value 1, found in four operating conditions denoted by the dots in Fig. 6 show substantial differences among the four mechanisms.

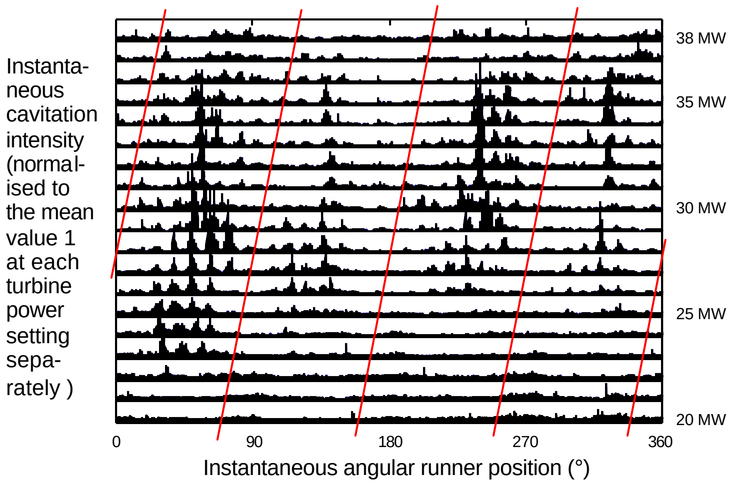

Fig. 9 – Recognisable traces of the action of the runner blades (the fields between the inclined lines) and the guide vanes (groups of peaks within the fields) are present in this log recorded by means of one sensor at a number of power settings. If the full set of such records from a sufficiently high number of appropriately spatially distributed sensors is analysed, reliable unbiased estimates of the total cavitation intensity due to the action of each guide-vane/runner-blade pair is obtained.

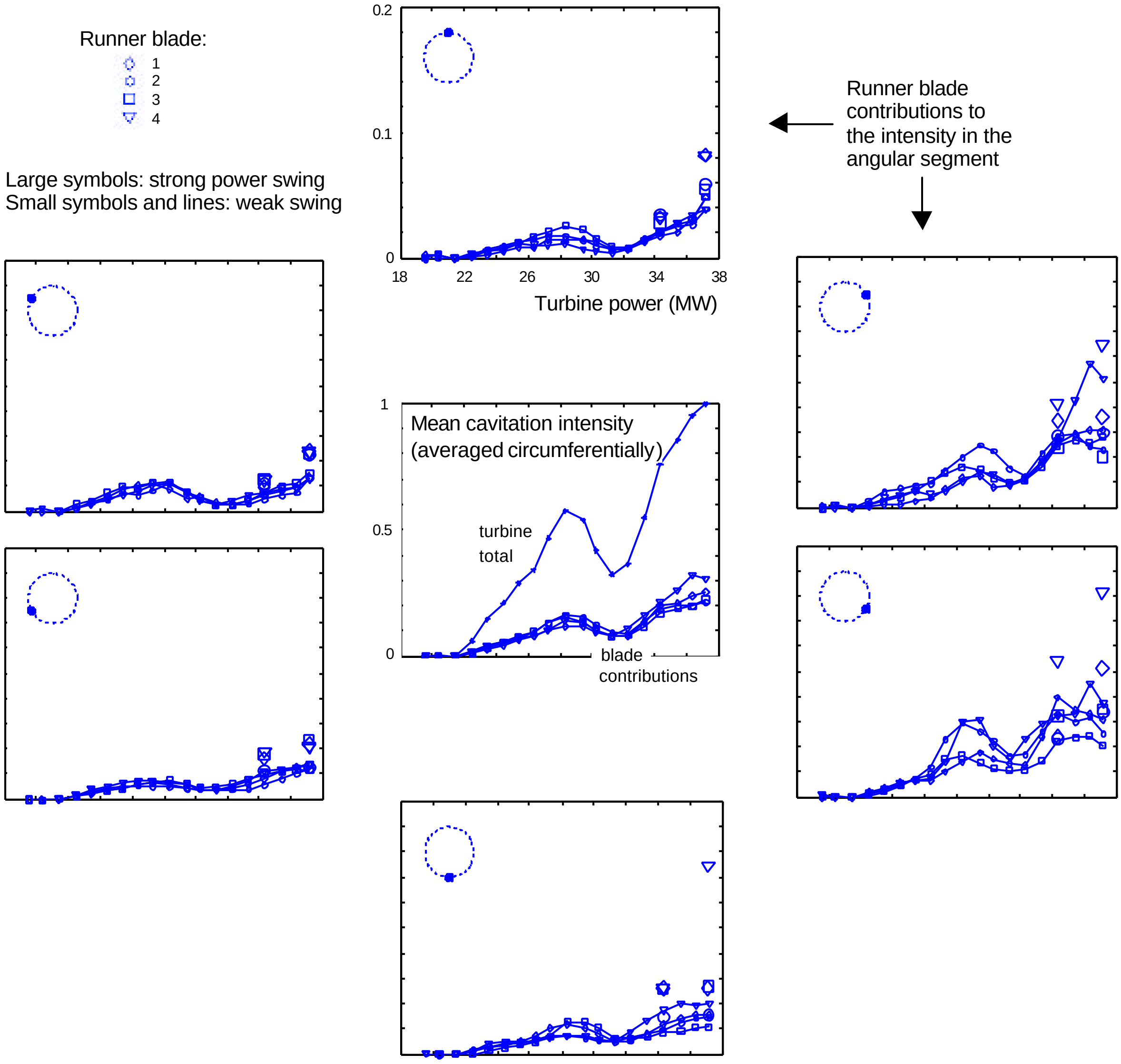

Fig. 10 - Cavitation intensity related to the four runner blades – their mean intensities (the graph in the middle) and the coarsely spatially resolved intensities (the six graphs around with denoted locations). The Dubrava unit A suffers from rather strong once-per-revolution power swing, the amplitude of which varies; two typical cases of this swing are considered.

Again, as in Fig. 6, the spatial resolution proved to be useful in the presentation in Fig. 10: while the four runner blades seem to cavitate almost equally strongly if judged by the mean curves, substantial differences among them are discovered by means of the resolved analysis. Indeed, cavitation provoked on blade 4 in the low pressure region (the upper right graph) is two times stronger than on the other blades.

4. Further effects

Incorrect guide-vane setting – A simulation of a malfunctioning guide vane was made on the Dubrava unit A. The opening of one vane was made 5° higher than normal. The effect on cavitation checked by a neighbouring sensor (Fig. 11): all the cavitation mechanisms were intensified but their thresholds stood unchanged, except for the highest-power one. Here, the threshold was substantially lowered (cf. the dashed lines).

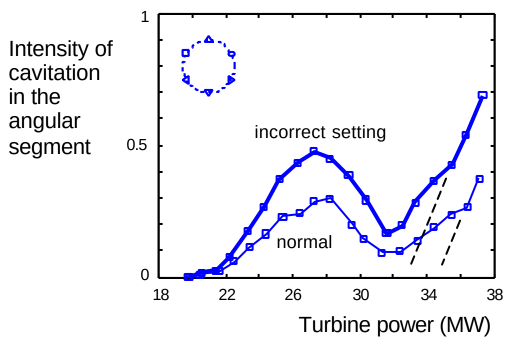

Fig. 11 - A case of a malfunctioning guide vane

Power swing – High correlation between the cavitation and the power swing, clearly expressed in Fig. 10 (compare the large and the small symbols), was further examined (Fig. 12). The strong cavitation on runner blade 4 and the power minimum were found to coincide. Both effects have the form of a once-per-revolution strike.

5. On cavitation in Dubrava unit A

Cavitation mechanisms – According to the model tests [7] at rated operating point, there was a safety margin of 3 meter water column between the critical cavitation coefficient of the turbine (-1 % in turbine efficiency) and the plant cavitation coefficient for the originally planned tail water conditions; rather highly developed cavitation was observed at this operating point. However, the turbine was designed and the model tests were carried out for the tail water 1.5 m higher than the actual one, as another plant was planned, but not built, immediately downstream. Further, these considerations are based on the cavitation coefficients at the axis. The dangerous upper positions are ca 2.5 metres higher, thus there is no reserve but instead the turbine operates –3+1.5+2.5 = 1 meter below the critical condition. Therefore, rather developed cavitation was allowed for in the project and even got worth due to the lower tail water. The appearance of the highest-powers cavitation mechanism within the normal operating range of the unit (Fig. 6) is attributed to this change in operating conditions. The existence of the other mechanisms and the small width of the cavitation optimum are due to the same reasons and the details of the runner blade form and sub-optimal cam.

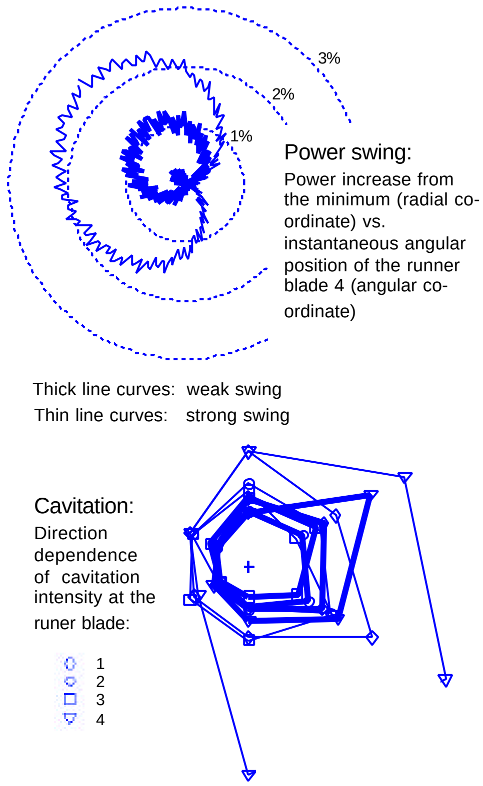

Fig. 12 – Strong power swing is accompanied by strong cavitation of runner blade 4, and these two effects have a similar distribution in space/time: both lie within a limited region/space, the power minimum and the cavitation intensity maximum fall into the approximately same direction (right down).

Cavitation erosion – The low power mechanism is harmless, the other three are erosive. Indeed, a visual inspection of the runner [8] revealed erosion to be traced back to each of these three mechanisms. Stronger erosion on runner blade 4 was found during the inspection; this is in accordance with the results of the vibro-acoustical diagnosis presented in Fig. 10.

Exceptional blade – A preliminary three-dimensional optical inspection of the runner blade geometry [9] showed differences that might explain the exceptional cavitation behaviour of the blade 4. A more detailed check of the leading edge shape is recommended.

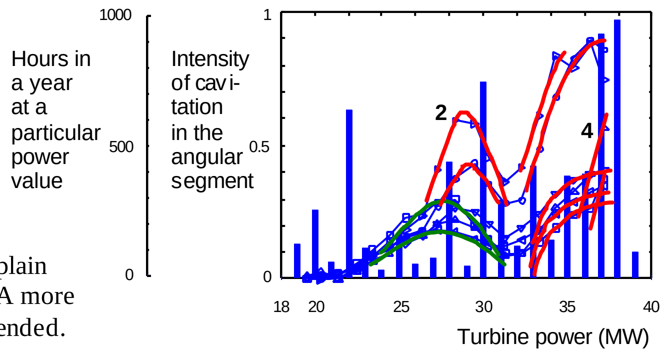

Fig. 13 - Unit operation can be optimised with respect to cavitation. Background: data from Fig. 6 and the yearly statistics of power settings (here: 6-year average).

Cavitation performance improvement – Improvements of the blade 4 geometry will make it similar to the other blades. Also, the cam has to be optimised; this should suppress the mid and high-power cavitation mechanisms. However, the overall cavitation characteristics of the turbine are not acceptable, and the required improvement might be obtained only by designing the new runner blades adjusted to the actual tail water and having profiles less prone to cavitation (weaker cavitation or none) and less sensitive to the inflow variations (broader cavitation optimum).

Operation optimisation – As can be seen in Fig. 13, the way the unit is operated is not optimal with respect to cavitation. The replacement of some of the frequently set power values with either somewhat lower or somewhat higher values (provided this is possible) can reduce the erosion by suppressing the cavitation mechanisms 2 and 4. The recommended changes are: 28 MW replaced by 26 MW, 30 MW by 32 MW, 37 MW and 38 W by 36 MW.

6. Conclusions

Diagnostic tests and monitoring of hydropower units, based on multidimensional analysis of data collected by means of an appropriate number of suitably located sensors and supported by empirical and theoretical models, yield an unbiased and rich description of the relevant dynamic processes, which may not be obtainable by other methods. This results in reliable diagnostics and monitoring that is highly sensitive to deterioration effects. In case of cavitation, the multidimensional approach enables identification of different cavitation mechanisms and yields assessment of cavitation quality of the individual turbine components. The multidimensional approach is well suited for investigation of the interplay between different processes in the hydro machinery.

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