Vibro-Acoustical Diagnostics of Turbine Cavitation Examples of Application*

By Branko Bajic, Korto Cavitation Services, Luxembourg
12, rue Ste Zithe, L-2763 Luxembourg phone +49 89 44450144 fax +49 89 44451325
korto@korto.com www.korto.com

ABSTRACT

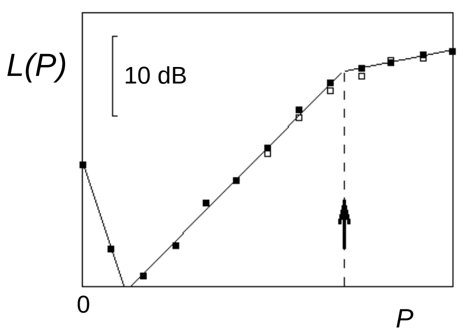
Practical applications of several recently-developed vibro-acoustical techniques for turbine cavitation diagnostics are illustrated: optimizing plant operation with respect to cavitation erosion, predicting change of accumulated erosion for new operating conditions, identifying turbine parts that are responsible for cavitation, identifying different cavitation mechanisms, deriving detailed cavitation characteristics of a turbine, and setting up a high-sensitivity cavitation monitoring system matched to a turbine.

Introduction

Several new techniques for vibro-acoustical diagnostics of turbine cavitation were introduced in the last five years [1-7]. They improved upon weak points and eliminated failures of some other techniques [6] and enabled distinguishing between different cavitation mechanisms and revealing the role played in cavitation by different turbine parts. The techniques were tested in prototype measurements on Francis, Kaplan, and bulb turbines. The types of results furnished by these techniques are illustrated in this paper.

Optimizing plant operation [1]

Cavitation erosion has been a problem in four 6 MW double-runner Francis turbines in a plant with a widely varying water supply in different periods of a year. In order to optimize plant operation with respect to erosion, a vibro-acoustical diagnosis of the 8 runners was made. The situation found at one of them is presented in the figure; *L* in *L(P)* is the logarithmically scaled cavitation intensity, and *P* the turbine power.



There is an abrupt change of the curve's slope at a certain critical power value (arrow) indicating the change of the cavitation mechanism. The mechanism functioning at higher loading may be assumed to be responsible for the erosion. Identical vibro-acoustical tests performed at eight (nominally identical) runners have revealed strong differences among them, and, in particular, the critical power values were different. These data and the data on the dependence of turbine efficiency on turbine power were used to define the plant operating plan

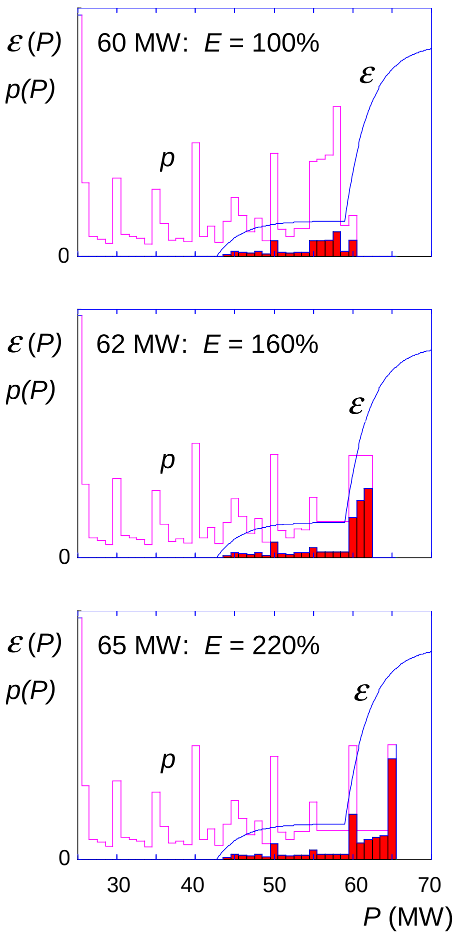
---

* Presented at the HydroVision 2000 Conference,
August 8-11, 2000, Charlotte, North Carolina, U.S.A.

that minimizes total erosion. This plan prescribes the number of turbines which should be used for a given total discharge, and the optimal distribution of their loads.

Predicting change of erosion [3]

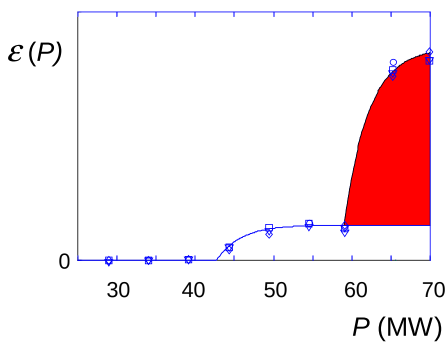
A 60 MW Kaplan turbine was experiencing cavitation damage in normal operation; the accumulated erosion was known from overhauls. A proposal was made to uprate the turbine by a simple increase of its load. A vibro-acoustical test was performed to predict the erosion for the new operating conditions and to determine if the uprating would be advisable.



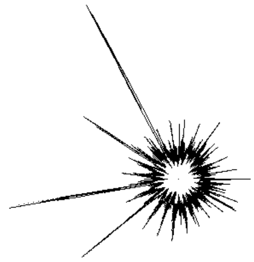
The result of the test was an estimate of the relative erosion rate, ε, as a function of the turbine power, P. In order to put this dependence, $\varepsilon(P)$, in a useful form, the accumulated erosion, E, was described by the integral of the product $p(P)\varepsilon(P)$, where $p(P)$ is the probability density function specifying the average use of the power value P, and ε was calibrated by scaling $\varepsilon(P)$ to make the integral to be 1 for the usual operation. Such an operation was described by the $p(P)$ calculated from the power statistics for a typical hydrologic year. This is as shown in the upper figure. The other two figures present the predictions of the erosion change for two hypothetical operation strategies in which the power of up to 62 MW or 65 MW would be reached. The filled histograms describe the contribution of a particular power to the accumulated erosion. The advisability of uprating the turbine follows from the cost analysis based on the derived E-values.

Identifying critical turbine parts [4]

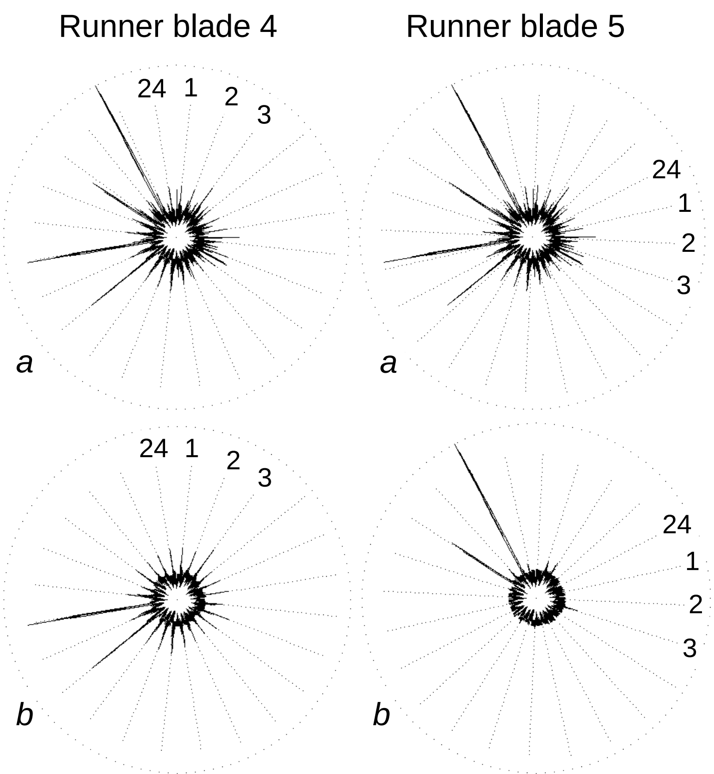
The diagnostic test of cavitation in a Kaplan turbine yielded the erosion-rate estimate, $\varepsilon(P)$, shown in the figure. Through modeling, the traces of which are also shown, the following description of the effects was derived: at the turbine power values below 43 MW there is no cavitation, at values higher than this there is one cavitation mechanism functioning, and at 59 MW or slightly higher another one starts. The filled area estimates the contribution of this second mechanism to the total erosion; this contribution can be up to 5 times



higher than the one of the first mechanism. The following question arose: *Which parts of the turbine are responsible for strong cavitation at high power values?* In order to answer this question, the frequency-resolved modulation analysis of cavitation noise was made. In a frequency band that is characteristic of the strong mechanism, the dependence of the mean noise power on the instantaneous angular runner's position was found as shown in the figure.



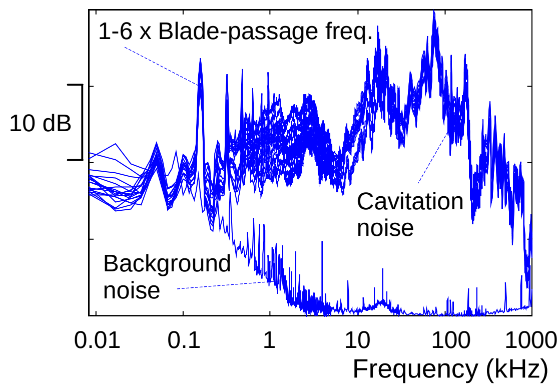
In the turbine considered, there are 24 guide vanes and 5 runner blades. This results in 120 special angular positions in which the traces of cavitation related to a particular guide-vane/runner-blade pair have to be expected. For the runner blades 4 and 5, these positions are presented in the following two *a*-figures, in which 1, 2, 3... 24 denote the traces of respective guide vanes.

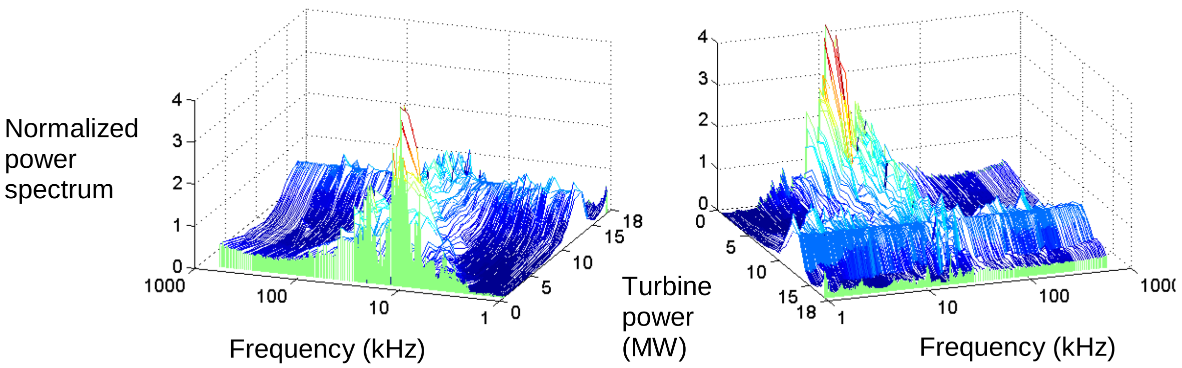


While the *a*-figures present direct measurement results, the *b*-figures are the estimates of the components that have to be attributed to runner blades 4 and 5. Since the two *b*-curves exhaust the original curve, these two blades suffice to explain the total effect. The *b*-figures reveal the role of the guide vanes, too: blade 4 cavitates behind all 24 guide vanes, strongly however only behind vanes 16 and 18; and blade 5 cavitates almost exclusively behind these two vanes. Therefore, runner blades 4 and 5 together with guide vanes 16 and 18 are responsible for strong cavitation. The other turbine parts may be considered good with respect to cavitation.

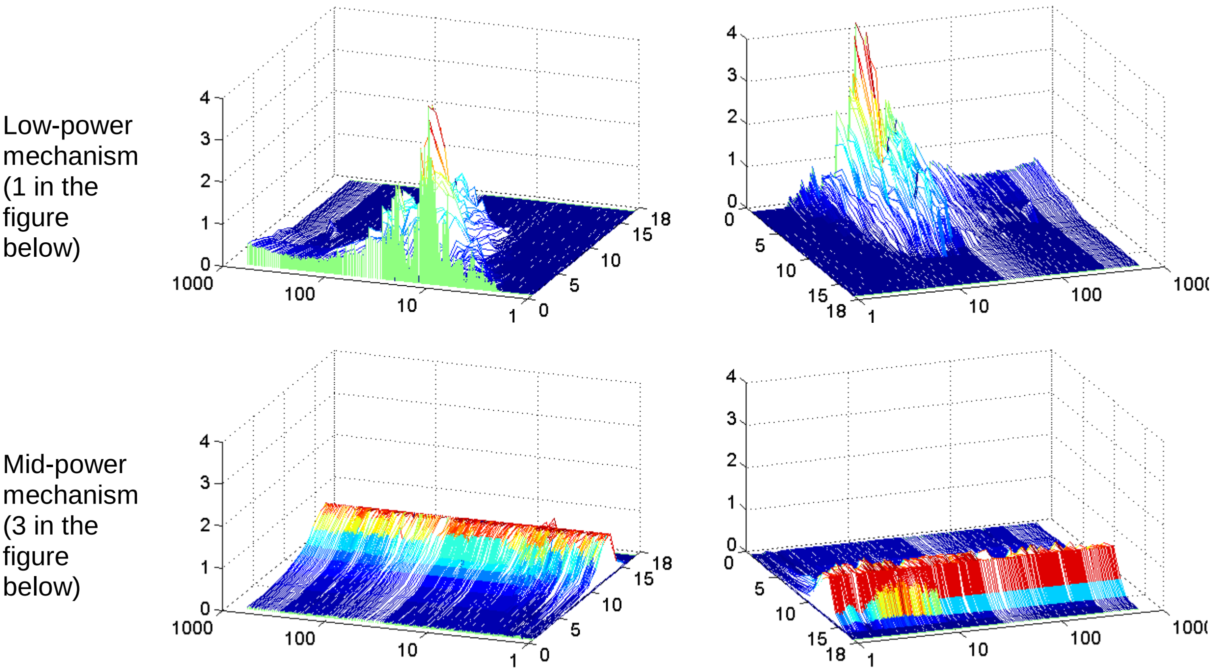
Identifying cavitation mechanisms [5,7]

From the raw cavitation noise spectra collected at various power values in a 17 MW Francis turbine as shown in the figure, hardly anything can be inferred. Although an extremely wide frequency band is covered, and the useful spectra lie sufficiently far from the background noise, not even qualitative conclusions can be deduced from the data in such a simple format.

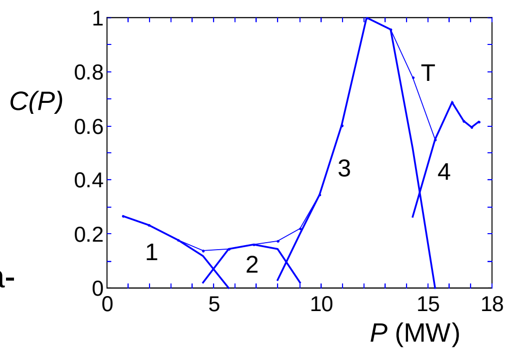




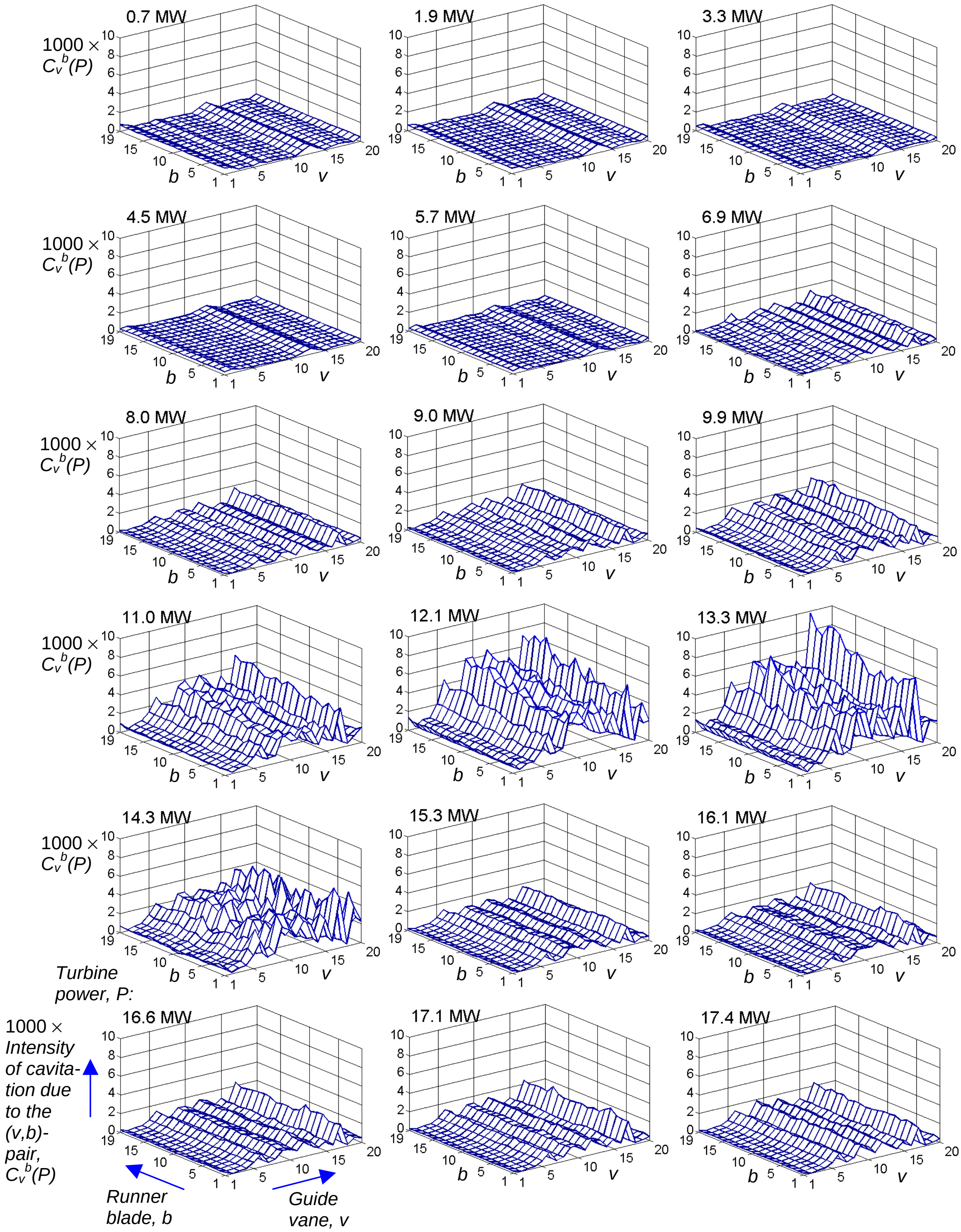
However, if transformed into a normalized form, which suppresses effects not related to cavitation [1], and displayed in a two-dimensional format (above), the same data enable a useful interpretation [7]. Indeed, by assuming that strongly differing spectra are related to different segments of the cavitation flow, cavitation mechanisms can be identified. Four mechanisms were found in the case considered; two of them are presented below.



Energy components represented by different spectra are not correlated, and thus are additive. Therefore, the cavitation intensity is the sum of the mechanisms' intensities. The resulting description for the turbine considered is shown here. T stands for the total intensity, and 1-4 are the contributions of the four mechanisms. It should be noted that not all the mechanisms are significant with respect to erosion.



Turbine cavitation characteristics [7]



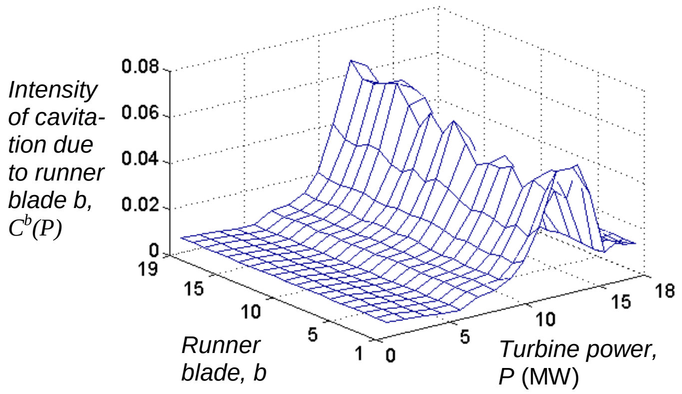
The multi-dimensional diagnostics of turbine cavitation [7] furnishes four types of turbine cavitation characteristics. They differ in the type and degree of resolution with respect to turbine parts, i.e. guide vanes, *v*, and runner blades, *b:*

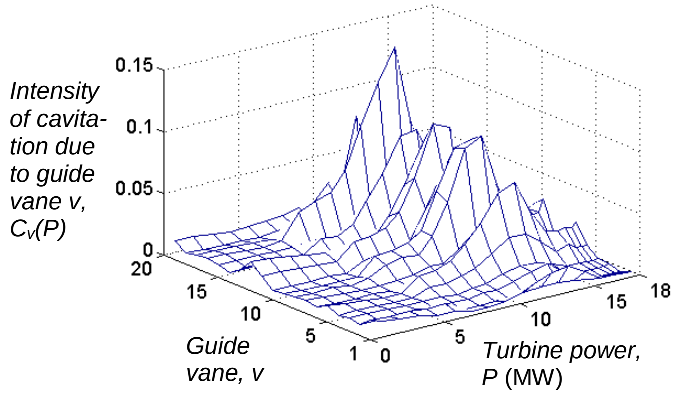
$C_v^b(P)$ *fine-structure characteristic,*

$C^b(P)$ *runner characteristic,*

$C_v(P)$ *wicket gate characteristic,*

$C(P)$ *global turbine characteristic.*





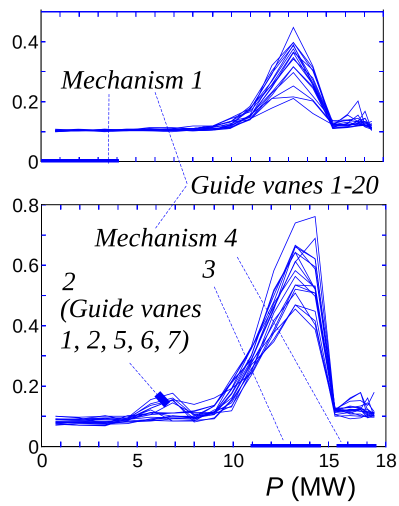
All of these specify the cavitation intensity for a given turbine power, *P*. The intensity is represented by a dimensionless quantity normalized so that the maximum total intensity equals 1. A quantitative relationship between cavitation intensity and loss of metal by erosion is out of the scope of the method, but the change of erosion rate and the change of the total accumulated erosion may well be assessed (see above the example on the prediction of erosion change). A typical use of the dimensionless cavitation intensity estimates is to compare cavitation at different turbine power values or cavitation caused by different turbine parts.

The four types of characteristics are illustrated by the *C(P)* diagram at the end of the example related to the cavitation mechanisms (global turbine characteristic), by the 18 graphs on the preceding page (fine structure characteristics), and by the two graphs above (runner and wicket-gate characteristics). They describe the 17 MW Francis turbine considered above. All the four types of characteristics may be defined in such a way as

- to describe the total cavitation intensity within a turbine, thus being a properly scaled sum of contributions of all the cavitation mechanisms, or
- to describe separately every mechanism appearing in the turbine.

With the exception of the global characteristic illustrated in the example on identification of the mechanisms, the other illustrations are related to the total cavitation.

Modulation depth of noise caused by different cavitation mechanisms, analyzed, for each mechanism, within a frequency band characteristic of it



The way in which cavitation intensity varies within a revolution and the degree of such variation can be used to (i) distinguish between different cavitation mechanisms, (ii) provide inference about their location, and (iii) assess their erosion potential. In the case discussed in the example illustrating the identification of cavitation mechanisms (see the global characteristic there), the analysis of the variation has revealed the existence of another cavitation mechanism that appears behind only five of 20 guide vanes (mechanism 2), and has shown that the mechanisms 2 and 3 are strongly influenced by the wake behind the guide vanes, while 1 and 4 are not. This is shown in the result of modulation-depth analysis presented above.

Cavitation monitoring

In the usual approach to cavitation monitoring, one measures, within a fixed frequency band, a chosen quantity that describes the mean total cavitation intensity – like noise level or rate of noise pulses, and sets a threshold for the measured quantity. Being based on respective mean values, such estimators cannot detect weak deviations from the normal state of the machinery, and thus may fail to detect early deterioration effects.

A much higher sensitivity with respect to both

(1) onset of cavitation, and,

(2) deterioration effects that occur during exploitation,

can be ensured if algorithms of the multi-dimensional diagnostics are built into the monitor. An illustration is presented on the next page (here P stands for a guiding vane, R for a runner blade). Three types of monitor outputs are shown:

(i) no resolution with respect to turbine parts,

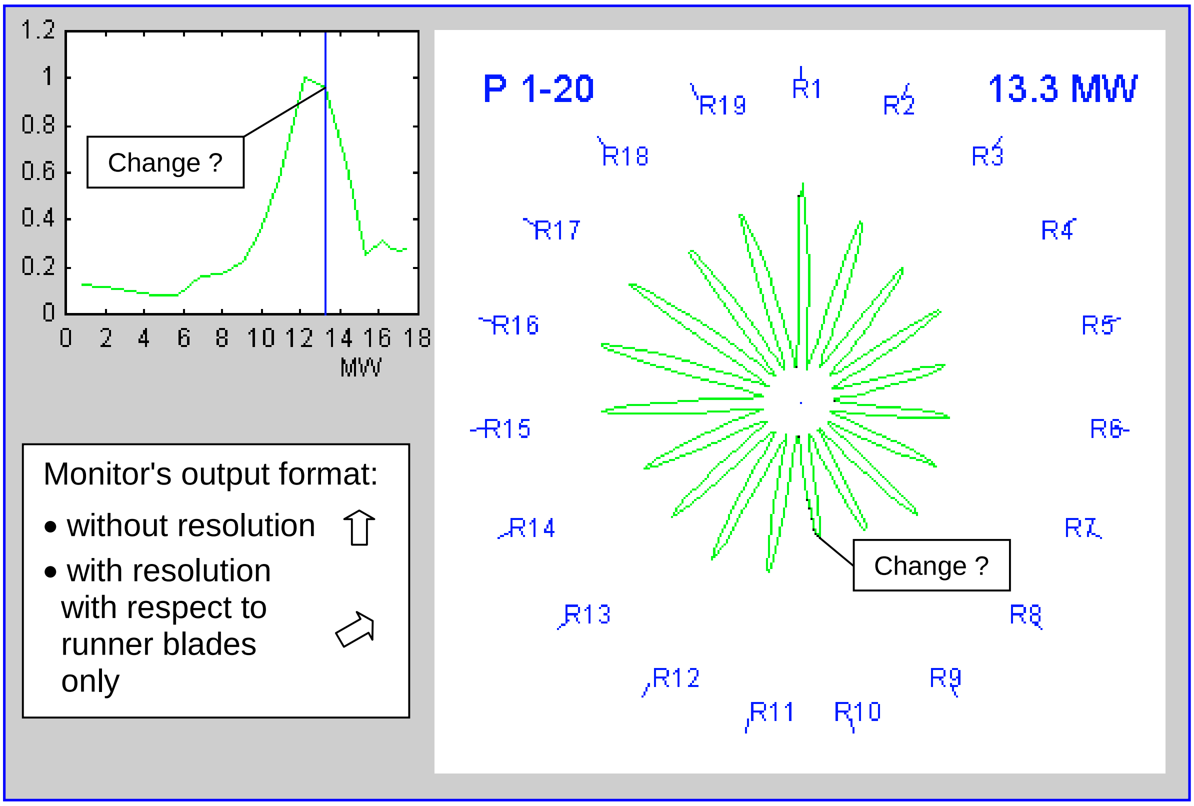
(ii) simple resolution (only with respect to runner blades),

(iii) double resolution (with respect to both runner blades and guide vanes).

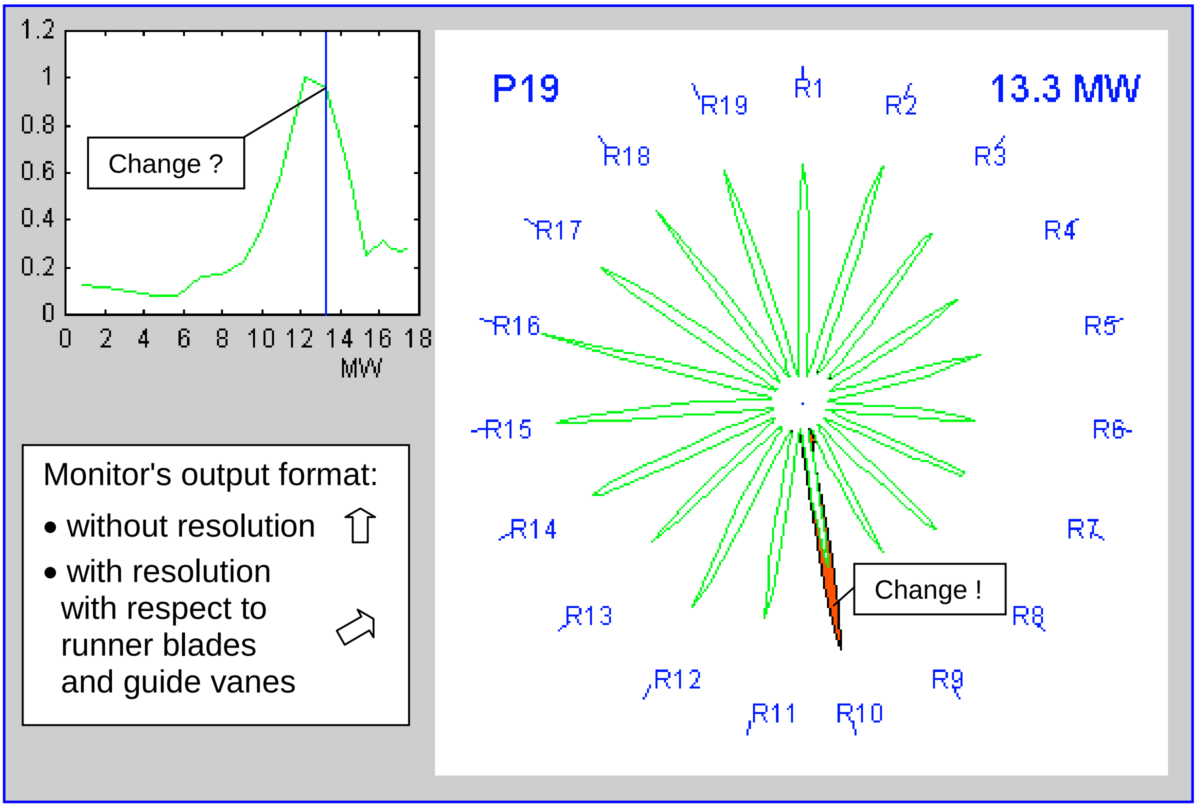
As can be seen, a change in cavitation that is easily detectable in format (iii), which is characteristic of the multi-dimensional algorithms, cannot be detected either in (i) or (ii).

Organization of turbine maintenance

Another disadvantage of the usual approach to cavitation monitoring is its lack of adaptability. Choosing the threshold value of the measured quantity does not suffice to optimize the monitor and have it match the peculiarities of a particular turbine. A ***tailor-made arrangement*** is the best way to set up a good cavitation monitor for a given turbine. To accomplish this, first one performs a ***detailed multi-dimensional diagnostic test*** and then chooses the monitoring algorithm and its parameters according to test results. It is even better not to rely upon an automatic monitor at all, but instead perform simple ***periodic checks*** after the detailed test has been made. In such checks one can adjust the measurement procedure to the actual results, react to new issues in the turbine's signature, and enlarge the scope of measurement if necessary.



1.2
1
0.8
0.6
0.4
0.2
0
0 2 4 6 8 10 12 14 16 18
MW
Change ?
Monitor's output format:
• without resolution
• with resolution with respect to runner blades only
P 1-20
13.3 MW
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10
R11
R12
R13
R14
R15
R16
R17
R18
R19
Change ?



1.2
1
0.8
0.6
0.4
0.2
0
0 2 4 6 8 10 12 14 16 18
MW
Change ?
Monitor's output format:
• without resolution
• with resolution with respect to runner blades and guide vanes
P19
13.3 MW
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10
R11
R12
R13
R14
R15
R16
R17
R18
R19
Change !

Conclusion

The recently developed multi-dimensional and other vibro-acoustical techniques for turbine cavitation diagnostics improved upon weak points and eliminated failures of some other techniques and introduced useful new possibilities. The techniques have been successfully tested in the following applications:

(1) optimizing plant operation with respect to cavitation erosion,
(2) predicting change of the accumulated erosion for new operating conditions,
(3) identifying turbine parts that are susceptible to cavitation,
(4) identifying different cavitation mechanisms,
(5) deriving detailed cavitation characteristics of a turbine,
(6) setting up a cavitation monitoring system that has an exceptionally high sensitivity with respect to deterioration effects in the early phases of their development.

References

1. Bajic, B., and Keller, A., Spectrum normalization method in vibro-acoustical diagnostic measurements of hydroturbine cavitation, Transactions of the ASME – Journal of Fluids Engineering, Vol. 118, 1996, pp. 756-761.
2. Bajic, B., Vibro-acoustical diagnosis of hydroturbine cavitation: Some measurement and analysis methods, Proceedings of the Conference Modelling, Testing & Monitoring for Hydro Powerplants II, Lausanne, Switzerland, The International Journal on Hydropower & Dams, 1996, pp. 169-178.
3. Bajic, B., A practical approach to vibroacoustical assessment of turbine cavitation, The International Journal on Hydropower & Dams, Vol. 3, 1996, pp. 45-50.
4. Bajic, B., Inflow decomposition: A vibroacoustical technique to reveal details of hydroturbine cavitation, Proceedings of the Conference Hydropower Into the Next Century, Portoroz, Slovenia, The International Journal on Hydropower & Dams, 1997, pp. 185-196.
5. Bajic, B*.,* Spectrum tracing - A vibroacoustic technique to identify mechanisms of turbine cavitation, Proceedings of the Conference Modelling, Testing & Monitoring for Hydro Powerplants III, Aix-en-Provence, France, The International Journal on Hydropower & Dams, 1998, pp. 641-652.
6. Bajic, B*.,* Neue Methoden der vibroakustischen Diagnostik der Turbinenkavitation, 10. Internationales Seminar Wasserkraftanlagen*,* Vienna, Austria, Vienna University of Technology, Tagungsband, 1998, pp. 447-458.
7. Bajic, B., Multi-dimensional diagnostics of turbine cavitation, 20th IAHR Symposium Hydraulic Machinery and Systems, Charlotte, North Carolina, USA, 2000.

Author

Dr. Branko Bajic is managing director of Korto Cavitation Services. He has many years of experience in research and practical work on vibro-acoustical phenomena of cavitation and is the author of a set of methods for vibro-acoustical diagnostics of turbine cavitation. Some of them are illustrated in this paper.