Turbine instability explained by multidimensional cavitation diagnostics

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Introduction

Since commissioning in 1989, the two 40 MW bulb units of the **Dubrava HPP** on the Drava River in Croatia have suffered from once-per-revolution power fluctuations, rather strong at unit A and somewhat weaker at unit B. These fluctuations cause increased dynamic loading on the machinery elements and thus shorten the units' life. From 1990 to 2002 numerous assumptions about the cause of the fluctuations were investigated [1-11]. Finally, in 2002 the explanation presented here was formulated and proven.

Vibro-acoustic diagnosis of cavitation in unit A turbine* which was carried out by Korto Cavitation Services' multidimensional method [12, 13] (Fig. 1), has shown that a connection between cavitation and the power fluctuations might exist [13]. Following that, by using experimental data on the power fluctuations collected in one-month monitoring [14] and data on cavitation in turbine A – collected in full-scale [13] and model-scale tests [15,16] – this possibility has been analysed in detail. One of the goals of the analysis was to find out to which extent the power fluctuations are the result of the fact that, since the planned downstream power plant has not been built, the Dubrava turbines operate at circa 1.5 m lower tail water than designed.

This is a report on the results of the analysis. First, the diagnosis is presented, then the arguments the diagnosis is based on, and, at the end, the practical implications of the findings, including the influence of the tail water.

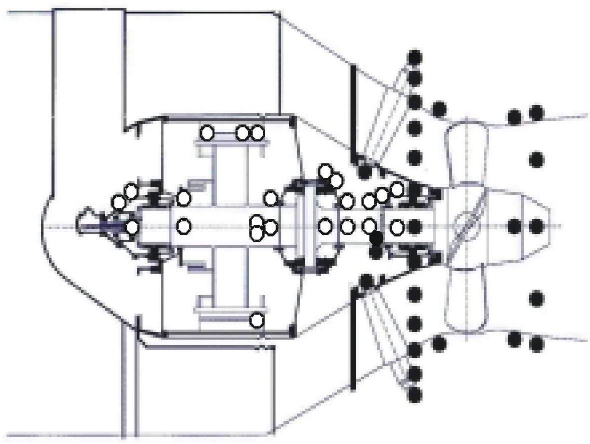

Fig. 1 - Dubrava HPP unit A with sensors used in the multidimensional diagnostic tests. In the diagnostics of cavitation and power fluctuations the sensors marked by solid dots and sources of data on operating conditions were used.

Diagnosis

Power fluctuations in the Dubrava HPP unit A are caused by cavitation which, due to the horizontal position of the shaft and a large runner diameter, pulsates once per revolution. The fluctuations become strong when strong sheet cavitation develops on the runner blades and especially strong when trash is caught on the guide vanes – especially the upper ones; this disturbs the inflow to the runner and thus intensifies cavitation development. The runner blades differ in cavitation quality; one blade cavitates especially strongly, which results in once-per-revolution rate.

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* Basic data on the turbines: power 40 MW, head 17.5 m; discharge 250 m³/s; rotation speed 125 min^{-1}; runner diameter 5.4 m; number of runner blades 4; number of guide vanes 24.

Experimental data

Power fluctuations

By monitoring power fluctuations, which included a large number of different operating conditions of unit A [14], the following two classes of power fluctuations (in accordance with the plant staff observation [17]) were identified:

- weak fluctuations which are permanent, and
- strong fluctuations which appear at unpredictable moments and can only be eliminated by stopping and restarting the machinery, not by taking it to speed-no-load or by mechanical turning; during the monitoring [14] one case of strong fluctuations was recorded.

Power-dependence of the fluctuations recorded is shown in Fig. 2, and Fig. 3 illustrates the waveform of the varying component of the instantaneous power.

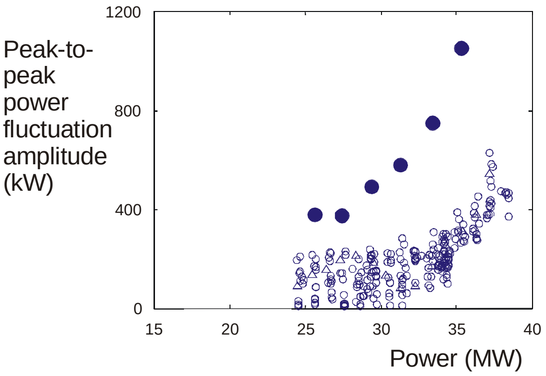


Fig. 2 - Measured power-dependence of the periodic component of the deviation of the instantaneous power from the mean value: hollow dots – weak fluctuations, solid dots – strong fluctuations.

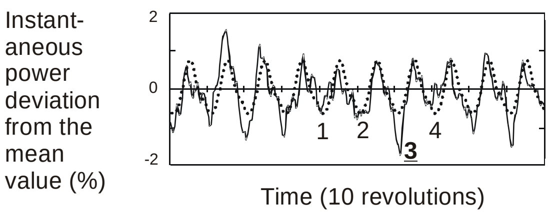


Fig. 3 - A typical waveform segment of the power fluctuations recorded at a high power value (solid line) and the approximation of its deterministic, slowly varying component (dots)

Cavitation

The multidimensional method for diagnostics and monitoring applied in the cavitation tests [13] enables space resolution of cavitation, resolution of cavitation close to individual runner blades, distinction between different cavitation mechanisms, as well as combinations of procedures. With a rough space resolution (in angular segments within the turbine), the test results are presented in Figs. 4-7 [13]; Figs. 4-6 refer to the normal state of the turbine and Fig. 7 to the state with a simulated failure, which illustrates the influence of a non-uniform inflow on cavitation. In the figures, cavitation intensity is represented by a vibro-acoustic quantity which is defined in the same way for all types of cavitation and is proportional to the erosion rate in case of erosive cavitation.

Analysis

Process dynamics

The estimate of the periodic component of the measured power fluctuations waveform shown in Fig. 3 (dots) can be used as a kind of reference in assessing the speed of change of the measured power fluctuations. As can be seen in the sequence of the periods 1-2-**3**-4, the change of the instantaneous power value is very fast: a significant power deviation from the mean trend occurs within a single revolution. Two direct conclusions can be drawn: (a) this is too fast for any resonant mechanism generating a once-per-revolution basic period; (b) cavitation, for which it is typical to vary substantially within a part of revolution as a reaction to random or deterministic variations in inflow, can – as far as variation speed is concerned – cause the phenomenon such as 1-2-**3**-4.

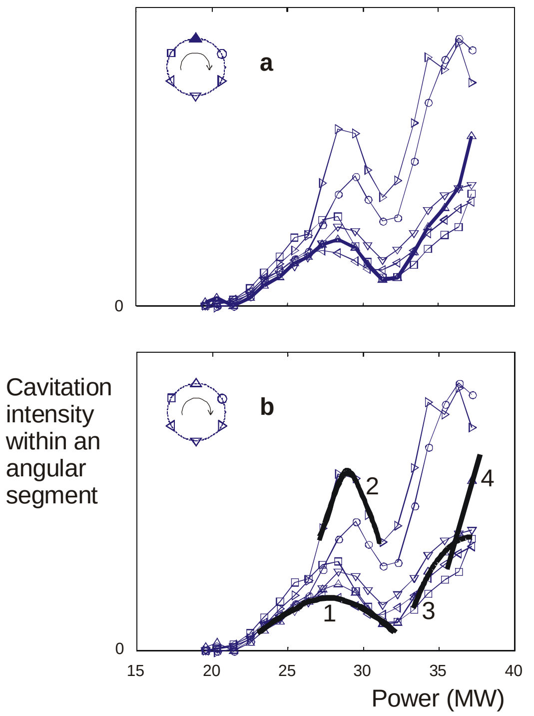


Fig. 4 - Cavitation intensity in 6 angular segments of the turbine denoted by 6 different symbols (downstream view; the arrow denotes rotation direction) [13]. In figure ***a*** *the upper angular segment with the lowest pressure is marked by the solid line, and in figure* ***b*** *traces of four cavitation mechanisms appearing in the turbine are shown.*

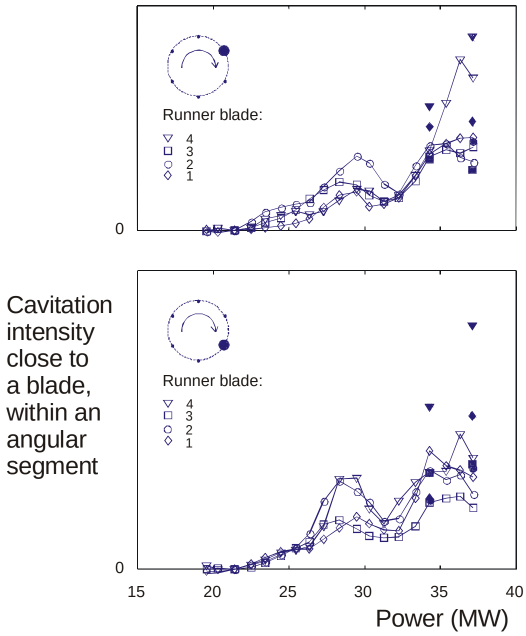


Fig. 5 - Cavitation intensity close to each of the 4 runner blades in two angular segments – upper right and down right [13]:
hollow symbols and lines – weak fluctuations regimes,
solid symbols – strong fluctuations regimes.

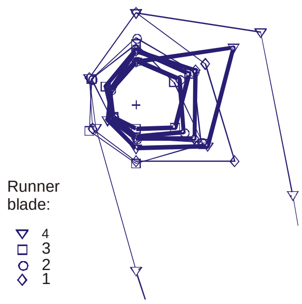


Fig. 6 - Cavitation intensity close to each of the 4 runner blades (radial co-ordinate) in relation to the instantaneous runner angular position described by the position of the blade 4 (angular co-ordinate) [13]:
thick lines – weak fluctuations,
thin lines – strong power fluctuations.

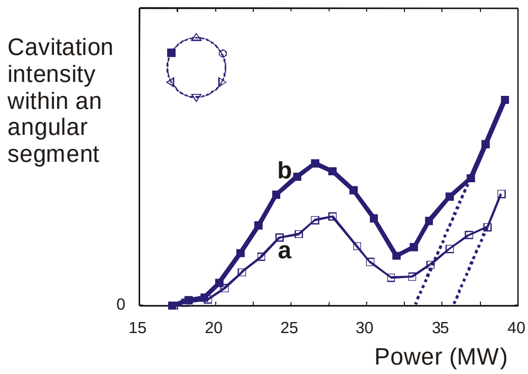
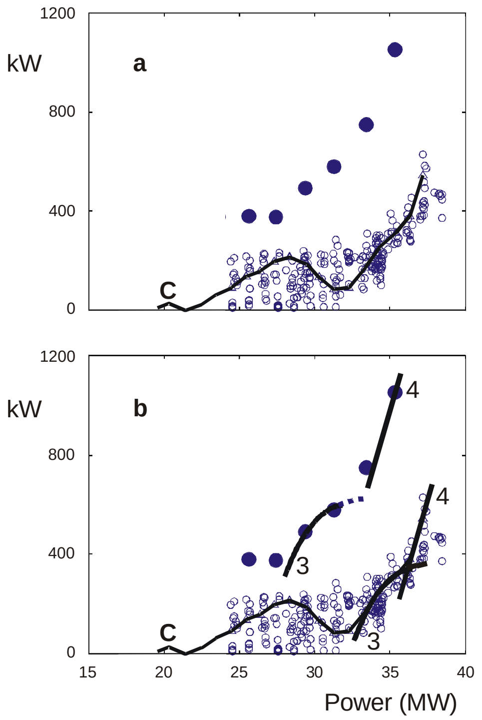


Fig. 7 - Influence of the incorrect guide blade position [13] – cavitation intensity in the angular segment behind a blade which is open for 5° more than needed:
(a) normal position of the blade,
(b) incorrect position.

Power dependence

The comparison of the power-dependence data on the power fluctuations and the cavitation, derived from Figs. 2 and 4 and shown in Fig. 8, displays a good correlation between the characteristic forms of this dependence. Indeed, at high power values, where power fluctuations are the strongest, they follow the characteristic non-monotonous form of the cavitation power-dependence (Fig. 8a). Further, the traces of cavitation mechanisms acting at the high and the highest power values can also be seen (Fig. 8b).



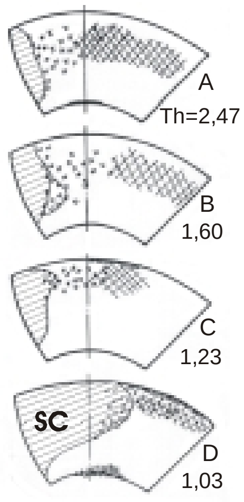


Fig. 9 - Cavitation forms close to the nominal head and discharge values as found in model tests for the Dubrava turbines at four values of the cavitation coefficient, Th [16]. Various types of cavitation present vary in erosion intensity; sheet cavitation (SC) is not particularly dangerous.

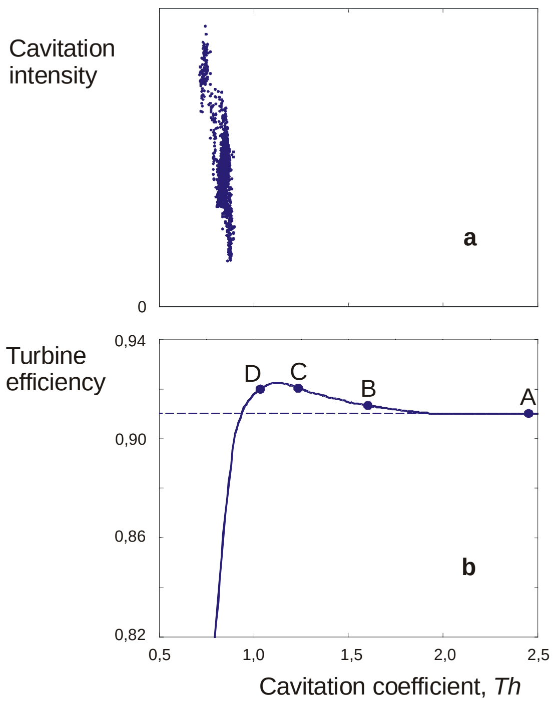
Fig. 8 - Data on the power-dependence of the power fluctuations amplitude (from Fig. 2) compared with the data on the power-dependence of the cavitation intensity:
***(a)** fluctuations compared with cavitation intensity dependence in the upper angular segment (curve C taken from Fig. 4a),*
***(b)** weak and strong fluctuations in comparison with the forms of the power-dependence of the cavitation mechanisms (mechanisms 3 and 4 from Fig. 4b)*

Dependence on runner position

The form of the dependence of the cavitation intensity on the instantaneous angular position of the runner, Fig. 6, or, more precisely, the difference of this form for weak and strong power fluctuations shows that there is a connection between cavitation and strong fluctuations, and that the time variation of this process has a typical rate: once per revolution, within a small part of a revolution, the cavitation intensity grows explosively when the power fluctuates strongly.

Interpretation

Figs. 9 and 10b show the results of the HPP Dubrava turbine cavitation model tests carried out in Turboinstitut, Ljubljana, Slovenia [15]; cavitation form sketches A-D in Fig. 9 refer to the equally marked operating points in Fig. 10b. Here, the cavitation coefficient, *Th*, is defined as the ratio of the pressure difference at a representative position and the critical pressure, both expressed in water column heights, to the head; the



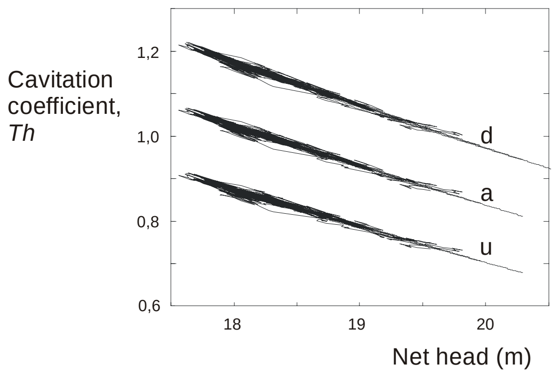


Fig. 11 - Survey of the Dubrava operating conditions: cavitation coefficient at the axis (a) and on the runner blade top when it is down (d) or up (u), in relation to the net head, for a typical head water

Fig. 10 - Results of full-scale vibro-acoustic tests of the cavitation intensity dependence on the cavitation coefficient in Dubrava turbine A (a), and model-scale results on the cavitation influence on the turbine efficiency for Dubrava at the head and discharge close to the nominal values [15] (b)

critical pressure is approximated by the water vapour pressure at a given temperature. In the full-scale test (Fig. 10a), where *Th* variations are high due to the shaft horizontal position and a large runner diameter, as a physically representative position for the *Th* estimate, the top of the blade in its upper position is taken.

Abrupt turbine efficiency drop with *Th* falling below a threshold (Fig. 10b) is followed by rapid growth of vibro-acoustically described cavitation intensity (Fig. 10a). Fig. 9 shows that these effects are the result of a strong development of the sheet cavitation, denoted by SC in the figure. At a heavy loading, at a low value of the cavitation coefficient, a large surface of the runner blade is affected by SC so that the lift is appreciably reduced. This reduces the contribution which a blade gives to the torque, and a measurable result is the instantaneous drop of the turbine power. A trace of the SC in the results in Figs. 4 and 8 is a mechanism at the highest load – mechanism 4: in addition to the cavitation coefficient, development of the SC depends very much on the blade loading as well.

A review of the full-scale cavitation conditions in Dubrava turbines, given in Fig. 11, shows that the blade tip and blade's parts at higher radii pass regimes with very low cavitation coefficient, below the efficiency curve threshold in Fig. 10b. The result is a strong SC cavitation development noticeable through the vibro-acoustically detected mechanism 4.

Cavitation conditions vary periodically since each part of the blade goes, within the revolution, through the positions between the appropriate maximum and minimum of the cavitation coefficient (the blade top between **d** and **u** values in Fig. 11), thus SC cavitation pulsates. Since cavitation is random, these changes are not strictly periodic.

If the cavitation quality of all runner blades were equal, the cavitation intensity and efficiency variations would have a typical rate of 4 times per revolution. However, since the blades are different with respect to cavitation (Figs. 5 and 6) so that cavitation at one blade, blade 4, reaches the highest intensity, much higher than at the others, a typical once-per-revolution period is obtained, the one that is noticed in the power fluctuations measurements. It is worth noting that the blades' geometry and their settings are within the margin defined by the standard; this obviously is not sufficient to provide uniformity of the cavitation quality.

A peculiarity of the strong power fluctuations that they occur only occasionally and cannot be eliminated by taking the unit to speed-no-load, but only by stopping and restarting the unit, can be explained by the effect similar to that in Fig. 7. Trash gets caught by a guide vane and can be removed only by stopping and re-starting the unit. The trash disturbs the inflow to the runner blades. This intensifies cavitation in the trace of the guide vane that caught the trash, which then produces a drop of runner blade lift, and thus a drop of tur-bine torque and power generated. As shown in Figs. 5 and 6, especially strong cavitation is developed in this manner on one blade, the worst one, blade number 4; the next one in cavitation quality, blade 1, follows it. The trash acts the strongest if caught by some of the upper guide vanes since there two effects support cavi-tation development, the distorted inflow to the runner and the low pressure. An alternative interpretation, according to which the trash caught by some of the four runner blades causes strong cavitation when it comes to the upper position, is eliminated by the fact that the fluctuations phase is permanent.

Strong cavitation and the efficiency drop, as described above, last only for a part of the revolution; this oc-curs when the outer parts of blade 4 are in the low-pressure region. Due to the inertia of the cavitation dy-namics, its full development comes after passing through the critical, upper position, i.e., when a bad blade is already in a position slightly shifted in the direction of rotation. Vibro-acoustically, it is observed even later (Figs. 5 and 6), when a large cavitation sheet, on its way out from the low pressure area, breaks down and disappears.

As shown in Fig. 8, this interpretation can be extended to the weak fluctuations, and the difference between the strong and weak one is only quantitative. Indeed, in both the strong and weak fluctuations, mechanisms 4 and 3 take part. However, if the curves 3 and 4 (Fig. 8b) are extrapolated to the maximum power, one can see that the 4 dominates in the strong fluctuations and the 3 is not significant, while, in case of the weak fluctuations, the 3 cannot be neglected. Further, also in case of less developed cavitation, the worst blade prevails so that weaker fluctuations have also a dominant once-per-revolution rate.

Process model

Differences in the cavitation quality of the runner blades, as seen in Figs. 5 and 6, can be modelled by shift-ing the efficiency curve in Fig. 10b along the cavitation-coefficient axis: the same degree of cavitation de-velopment appears at different blades at different cavitation coefficient values. Further difference among the blades can be described by a characteristic radius at which a dominant cavitation reducing efficiency is de-veloped. Accordingly, the efficiency functions like the one in Fig. 10b, $\eta = \eta(H,Q,Th)$, where η is effi-ciency, H head, Q discharge, and Th cavitation coefficient, can be written for particular blades, n = 1,2,3,4, in dependence on the instantaneous angular position of the runner blade θ, like $\eta_n = \eta(H,Q,Th(\theta\text{-}n\pi/2\text{-}\theta_o,r_n)\ \text{-}\delta Th_n)$, where $Th(\theta,r)$ is the cavitation coefficient on the radius r when the runner is in the position θ; r_n the charac-teristic radius of the blade n; and δTh_n the above mentioned shift in Th of the efficiency curve, describing the blade n quality. By modelling cavitation development delay after the cause by θ_o, the basis of the simulation model of the power fluctuation process in accordance with the above noted interpretation is formally prepared.

Further, one assumes that the component of the moment contributed by the blade n is proportional to η_n, and a quarter of the sum of η_n of all four blades, $\eta(H,Q,Th_{ref},\theta)$, marked by a reference value of Th, Th_{ref}, e.g. the one on the axis, is observed as a quantity proportional to the total torque and power. Thus, the instantaneous relative power value in the moment when the runner is in θ equals $\eta(H,Q,Th_{ref},\theta)/\langle\eta(H,Q,Th_{ref},\varphi)\rangle_\varphi$, where $\langle f(\varphi)\rangle_\varphi$ stands for averaging $f(\varphi)$ over $\varphi\in[0,2\pi]$. Deviation of this quantity from 1 is the instantaneous rela-tive power deviation from the mean value with the runner in θ, while the difference between a minimum and a maximum (in θ) of that quantity is the relative peak-to-peak amplitude of the power fluctuations in the operating point (H,Q,Th_{ref}).

The presented model of the phenomenon is deterministic. Thus, it delivers a periodic description of the cir-cumstances and refers only to the periodic component of the fluctuations, not to random deviations from it.

Simulation

Simulation of the power fluctuations is carried out by means of the described model. The same characteristic radius r_n, equal to 70% of the runner blade radius, is assumed for all blades, n =1,2,3,4. The shifts δTh_n are estimated on the basis of differences in vibro-acoustically assessed intensity on different blades of mecha-nism 4 at the highest power, according to Fig. 5. It is assumed that the best blade follows the behaviour of the model, while for the others, the shifts δTh_n were estimated on the basis of intensity differences in relation

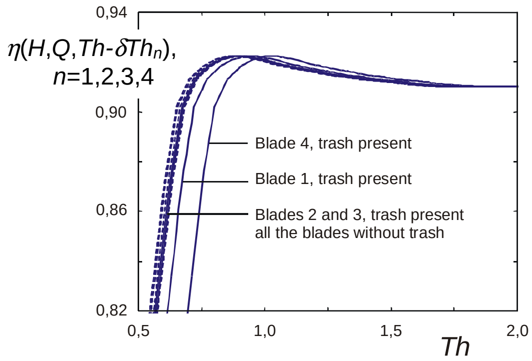


Fig. 12 - Cavitation quality of the runner blade assessed by means of vibro-acoustic cavitation intensity estimates; the best blade is assumed to follow behaviour found by the model testing.

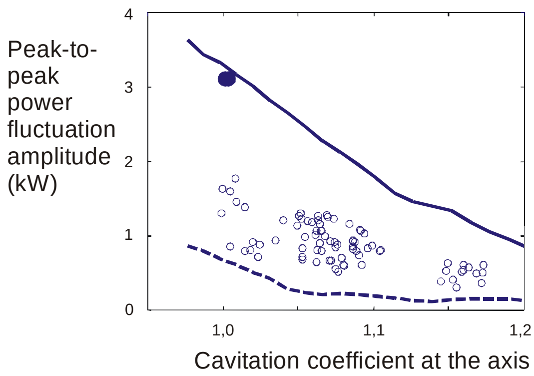


Fig. 13 - Simulation results (lines) and measurements (dots):
the solid line and the solid symbol – strong fluctuations (trash on the guide vanes acts);
the broken line and the hollow symbols – weak fluctuations (without trash).
This description is valid for high power values at the head close to the nominal one.

to the best one through straight line-modelled dependence from Fig. 10a; the result is shown in Fig. 12. This description and the results thus obtained refer to the head and discharge close to the nominal values, since the model description of the conditions in Figs. 9 and 10b is related to them.

A comparison of the measured power fluctuations amplitude with the one obtained by the simulation based on the noted parameters is shown in Fig. 13; here, global cavitation conditions in the turbine are described by the cavitation conditions on the axis. It is evident that the model of the weak fluctuations gives only the lower limit of the amplitude (mechanism 3 becomes important and is not well described by the process model used), while the strong fluctuations model is derived from the example of the strong fluctuations recorded during monitoring [14] and they thus agree. If the unrealistic assumption of equal values of the characteristic radius r_n for all the four blades is omitted, the simulation can give a good prediction of the power fluctuations waveforms, Fig. 14.

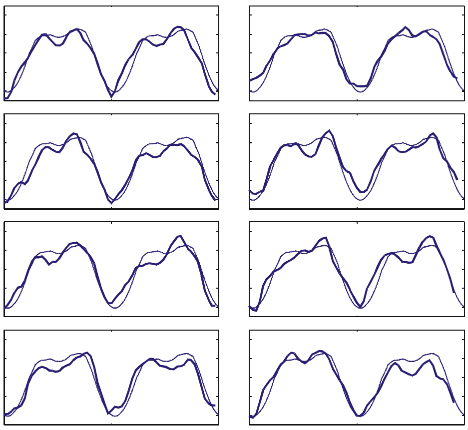


Fig. 14 - Waveform of the instantaneous power deviation from the mean value found in the case of strong fluctuations in 8x2 subsequent revolutions: thick line – measured, thin line – simulation result

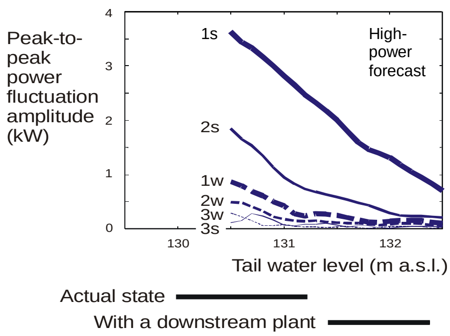


Fig. 15 - Assessment of the runner quality regarding power fluctuations at high power values and a typical head water:
1 - actual machinery state,
2 - the worst blade repaired to reach the quality of the next one,
3 - all blades like the best one;
s - trash acts (strong fluctuations),
w- no trash (weak fluctuations)

Runner quality assessment

The simulation results in Fig.13 for a typical head water and a high power are presented in a more practical format in Fig. 15. Descriptions of some hypothetical situations are added here: repaired blades, the worst one or all of them, a tail water raised to the design elevation. Based on this figure and Figs. 9-12, the following conclusions can be drawn:

First. The runner blades that are good with respect to cavitation operate in the conditions with strong efficiency drop even without the thrash caught by the wicked gates. The runner blades which have failures in geometry due to inaccuracy in manufacturing, operate deep in that regime. Such is the situation with the existing tail water, i.e., without downstream power plant.

Second. Higher tail water, for which the turbine is designed, would reduce strong power fluctuations amplitude to less than a half, even with the given geometry failures (Fig. 15, shift for 1.5m). However, the power fluctuations would still be rather strong.

Third. With the existing quality of the blades' geometry, at a lower tail water, with or without the downstream power plant, the strong fluctuations are inevitable when the upper guide blades catch the trash.

Fourth. Poor quality of blades, two of which, although within tolerances prescribed by a relevant standard, are bad with respect to cavitation, is decisive for fluctuations with or without trash. Even if the worst blade would be repaired, strong fluctuations are inevitable within the operation range of the turbine in the existing condition. Only when both bad blades reach the quality of the others, strong fluctuations can be eliminated, and only weak fluctuations would remain.

Therefore, regarding the power fluctuations, cavitation quality of the design as described by the model tests, would be sufficient for the operation in the conditions assumed in the design, i.e., with the tail water maintained by the downstream power plant but only if the runner finish is good, and if there is no trash on the guide vanes. The given cavitation quality of the design is not sufficient, without undue risk, whatever the accuracy of manufacturing that can be achieved in practice.

There are two aspects of the cavitation quality of the runner:
- resistance to cavitation expressed by the characteristic values of the cavitation coefficient and
- resistance to inflow variations.

The former describes cavitation quality of the runner in normal conditions, the latter along with the former the quality while operating with the trash on the wicket gate. With the trash present, the quality of the existing runner is not sufficient regarding either the first or the second aspect.

To summarise, imprecise manufacturing of the runner is responsible for power fluctuations, and its deterioration effects are made worse by the operation outside the design parameters and the fact that the runner design was risky with respect to cavitation.

Shaft vibration

Results of the four independent series of vibration measurements at the Dubrava unit A, presented in Fig. 16, show that the power fluctuations and shaft vibrations at high power values might have a common cause – developed pulsating sheet cavitation, different at individual runner blades and especially strong at one of them. In addition to the form of the power-dependence of the vibration amplitude at high power values (cf. Fig. 8 and 16), the fact that – like power fluctuations that strongly depend on cavitation conditions – the vibration component at high power values varies from one to another regime while the component at lower power values, caused by something else, remains the same, indicates that the shaft vibrations at high power values are caused by cavitation.

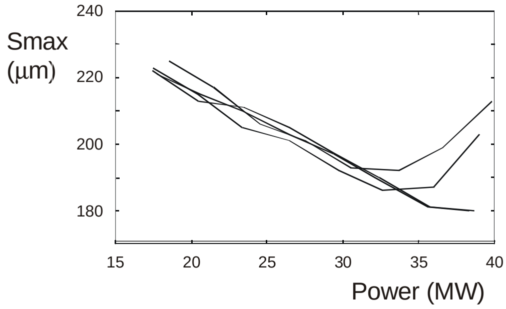


Fig. 16 - Shaft vibration amplitude of the Dubrava unit A downstream of the axial bearing at four different conditions [11].

Conclusions

The power fluctuations at the Dubrava HPP bulb units are caused by cavitation developed on the runner blades which, due to the shaft horizontal position and a large runner diameter, pulsate once per revolution. The fluctuations become strong when strong sheet cavitation is developed and especially strong when trash is caught by the upper guide vanes; this disturbs the inflow to the runner and supports cavitation development. It is interesting to note that cavitation causing these fluctuations is not very erosive.

Not sufficiently accurate manufacturing of the runner with respect to cavitation, even when keeping the runner shape within tolerances prescribed by a standard, is responsible for the power fluctuations. The tail water lower than designed and the runner design that is risky with respect to cavitation amplify the strong effects of imprecise manufacturing. However, the fluctuations would not be eliminated even under the design operating conditions, with the tail water higher by 1.5 m. The disadvantages of the design: it permits excessively strong cavitation under normal operation and results in an unacceptably high sensitivity to inflow variations.

The collected experimental data leads to the conclusion that the intense shaft vibrations at high power values have the same origin as the power fluctuations.

As the trash cannot be eliminated entirely, and as the runner shaped more accurately than that required by the standard is hardly feasible, strong fluctuations can be eliminated only by designing the new runner for a given tail water, such that would have a sufficient cavitation resistance and a low sensitivity to inflow variations. The owner has decided to follow this course of action.

Acknowledgement

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Dr. B. Bajic, managing director of Korto Cavitation Services, has extensive experience with vibro-acoustic phenomena of cavitation, dynamic process analysis, signal and data processing, and other attributes of monitoring system design and use. He authors several innovative methods for vibro-acoustic diagnostics and monitoring of turbine cavitation.