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EXPERIMENTAL ANALYSIS OF THE OPTIMAL CAM CHARACTERISTIC FOR A KAPLAN TURBINE

Georgiana DUNCA [1], Diana Maria BUCUR [1], Constantin CĂLINOIU [2],
Eugen Constantin ISBĂŞOIU [3]
[1]Lecturer, Power Engineering Faculty, University "Politehnica" of Bucharest, Romania, 313, Splaiul Independentei, Bucharest, Romania, dmbucur@yahoo.com, tel: 0040-214029523/fax: 0040-214029865
[2] Associate professor, Power Engineering Faculty, University "Politehnica" of Bucharest, Romania
[3] Professor, Power Engineering Faculty, University "Politehnica" of Bucharest, Romania

Abstract

In this paper the optimal CAM characteristic is determined for a unit of 22 MW with 12.5 m designed net head and 185 m^3/s rated discharge, in a run of river power plant.

Field tests aere performed, first in the conditions of the actual CAM, then with the CAM relation broken off. The efficiency is obtained at different runner blades and guide vanes opening combinations across a range of heads. The optimum three dimensional combination between the runner blades opening and the guide vanes opening, for different head values is determined to maximize the real operational efficiency.

The conclusion is that the efficiency in the conditions of the new CAM characteristic increased up to 2%, with a smaller opening of the guide vanes, which decreased from 6% to 9% of the total opening.

The results are confirmed analytically, by transposing the model theoretical efficiency curves to the real operational conditions (head and discharge).

The determination of the real efficiency curve and the optimal CAM characteristic is important also from the vibration point of view.

Keywords: CAM characteristic, Kaplan turbine, measurements, rated discharge, rated efficiency, vibration.

1. Introduction

Considering the present efforts for increasing the green energy production, one of the easiest things to do is to optimize the operation of the hydro units. For existing Kaplan turbines, index testing and optimization are the best way to assure the maximum efficiency and power output.

The necessity of analyzing the optimal CAM characteristic for this particular hydro power plant comes from the real on site operation conditions, which are different from those supposed when the plant and turbines were designed. In the initial project, the position of the runner referred to the downstream level is – 1.5 m to – 2 m. Because the next downstream dam is not yet built, the downstream level is lower than designed and the position of the runner is above downstream level at + 2 ÷ + 3 m. This changes totally the head of the turbines, from 12.5 m to 16 m, so the best efficiency point and the optimal CAM characteristic are different from those designed.

2. Experimental setup

Field tests are carried out on a hydropower plant (HPP) located on one of the internal rivers from Romania [1, 2]. The HPP is situated on the river stream. In figure 1 the reservoir and the dam are presented. Figure 2 presentes the HPP cross section.

The analyzed Kaplan turbine has 22 MW at 12.5 m rated head and 185 m^3/s rated discharge, in a run of river power plant [3]. In figures 3 and 4 the turbine runner and guide vane and the generator stator are presented.

Fig.1 – The HPP reservoir and dam

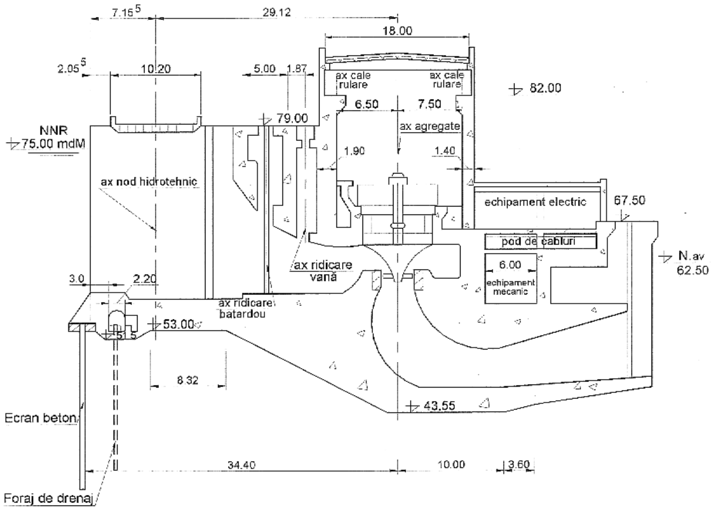

Fig.2 – HPP cross section

Fig. 3 – Turbine runner

Fig. 4 – Generator stator and turbine guide vane

3. Measurements

First, for a number of operating regimes with the actual CAM combination, the hydrounit efficiency curves (η) depending on reported discharge (Q^*) and the corresponding combination of guide vanes opening (S_{ad}) and runner blade angle (S_r), are determined.

In the second part of the tests, the CAM relation is broken and a series of operating regimes with constant runner blade inclinations reported to the maximum inclination (S_r =2.5%, S_r =15%, S_r = 25%, S_r = 37.5% and S_r =50%) are tested. For each inclination the variation of the flow parameters as a function of the reported discharge are measured for:

- the guide vane opening, S_{ad}, reported to the maximum opening;
- runner blades inclination, S_r, reported to the maximum inclination;
- the level after the upstream grill, Z_1;
- downstream level, Z_2;
- pressure difference indicated by the two pressure taps on the spiral case, Δh;
- electrical power, P_g.

The upstream and downstream levels are measured using the existing equipment on site.

The reported discharge, Q^*, is measured using a differential pressure transducer with a precision of 0.25 % (fig. 5), connected to the two pressure taps located on the spiral case. It is proportional to the absolute discharge, according to the equation

$$Q^* = k\sqrt{\Delta h} \quad [\mathrm{m}^{1/2}]. \tag{1}$$

Fig. 5 – Differential pressure transducer

Fig. 6 – Electrical parameters monitoring system

The electrical power is measured using a monitoring system, with a precision of 0.3%. It is presented in figure 6.

The guide vane opening**,** S_{ad}, and the runner blades inclination, S_r, are measured using the existing equipment on site.

The vibration of the turbine shaft and of the turbine cover are measured for both actual and broken-off CAM characteristic.

Shaft sensing proximity probes are used to obtain relative displacement measurements of rotating or reciprocating shaft surfaces. They are mounted in a traditional manner [3], the vertical probe being located directly above the shaft at 12 o'clock, and the horizontal probe on the right side of the shaft at the 3 o'clock position (fig. 7). The vibrations signals are acquired using a data acquisition system, with an acquisition frequency of 1000 Hz.

The turbine cover vibration is measured using an accelerometer. The main advantages of this kind of vibration transducers are that they measure casing or structural absolute motion and can be easily attached to structure. It is mounted on the turbine cover as shown in figure 8. The signal is acquired using a data acquisition system, with an acquisition frequency of 1000 Hz.

The first analized upstream level is the highest, 16 m, due to existing conditions. Then, the entire measuring procedure is repeted for the lower upstream level of 14.8 m. In the computation stage, the results for a third medium head of 15.4 m are determined by interpolation methods. Finally, the results covere all the operational domain.

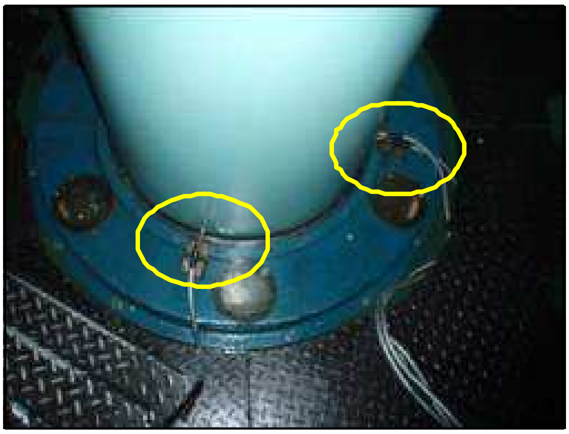

Fig. 7 – Vibration transducers setting on the turbine shaft

Fig. 8 – Accelerometer's location on the turbine cover

4 CAM characteristic

All the results are computed for the net head using the equations:

$$Q_c = Q\left(\frac{H_{nc}}{H_n}\right)^{1/2}, \tag{2}$$

$$P_c = P\left(\frac{H_{nc}}{H_n}\right)^{3/2}. \tag{3}$$

The following figures are presented for the higher upstream level, which corresponds to a 16 m net head.

The data obtained for the original CAM characteristic are presented in figure 9 – the reported efficiency curve and in figure 10 – the relation between guide vane opening**,** S_{ad}, and the runner blades inclination, S_r.

On the basis of data analyzed, efficiency curves are drawn, depending on the discharge and on power output, for each S_r (fig. 11). By drawing envelope curves around efficiency curves, optimal efficiency values are determined.

The guide vanes opening (S_{ad}) for each runner inclination are represented as a function of reported discharge and power output (fig. 12). By connecting the points corresponding to the best efficiency points for each S_r, the optimal CAM characteristic is obtained.

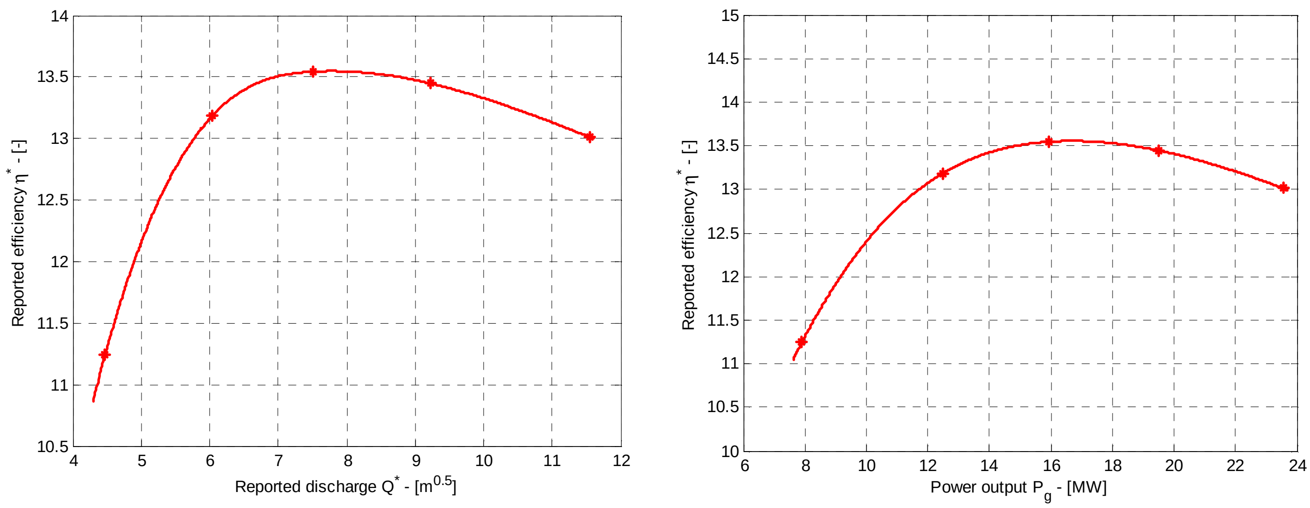

Fig. 9 – Hydro unit rated efficiency for the existing CAM relation

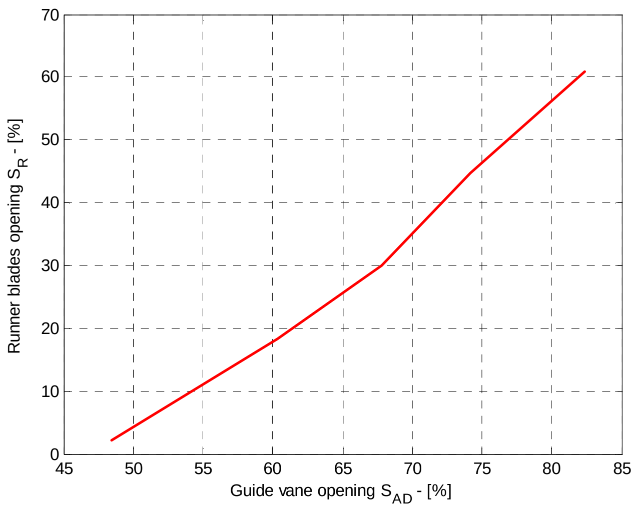

Fig. 10 – Actual CAM relationship

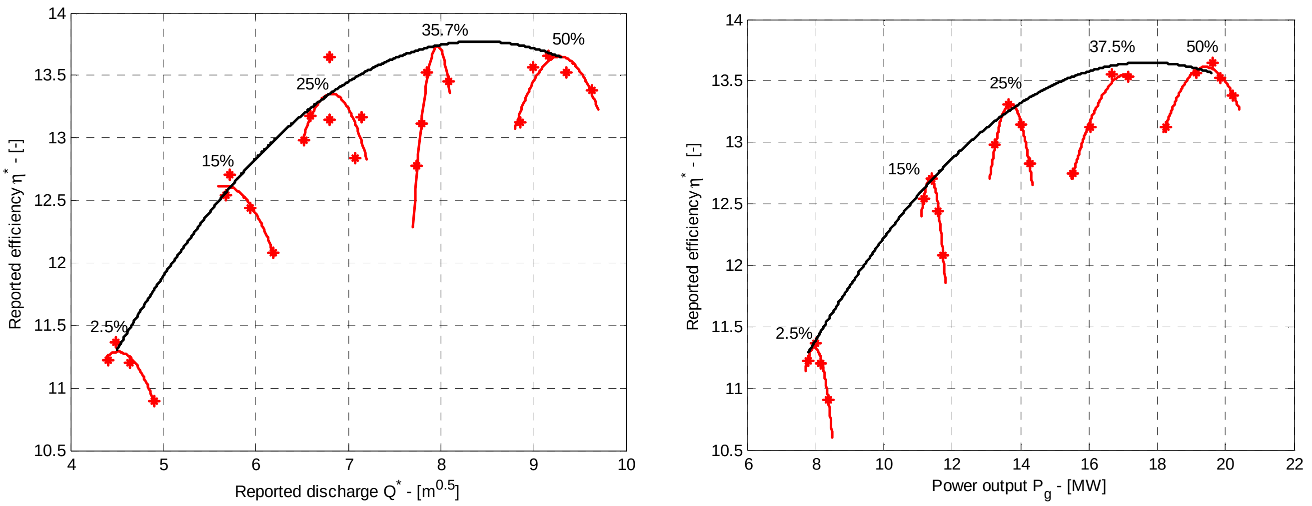

Fig. 11 – Rated efficiency for broke-off CAM combination with envelope curve defining optimal values

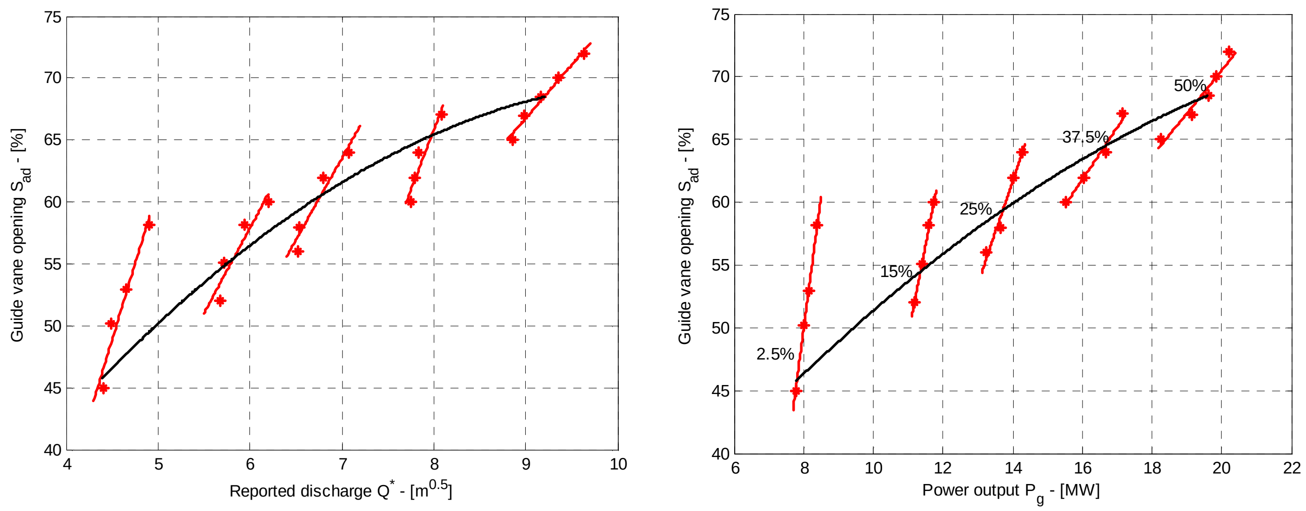

Fig. 12 – Guide vane opening at broke-off combination with envelope curve defining optimal values

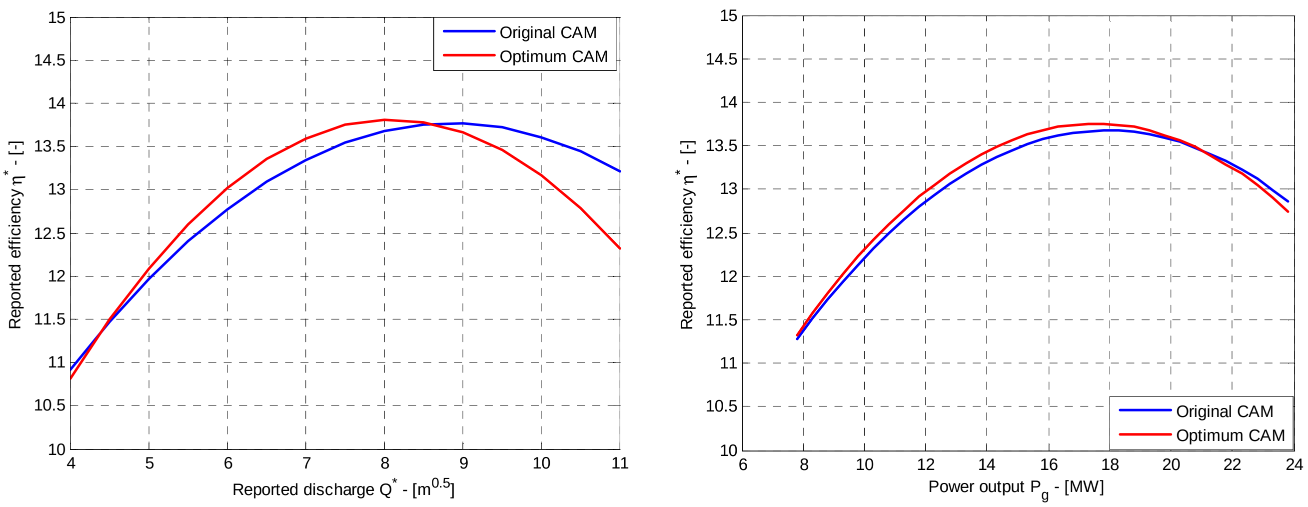

Fig. 13 – Rated efficiency for original and optimum CAM relation

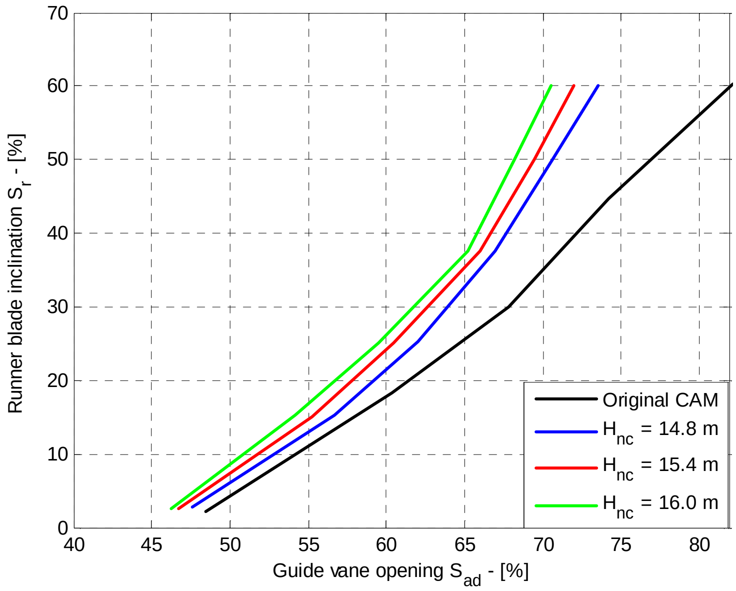

Fig. 14 – Original and optimum CAM combination

For the new CAM combination obtained, the efficiency is computed and compared to the original one (fig. 13). The rated discharge is smaller in case of the optimum CAM, which proves the importance of the tests.

The rated best eficiency point at 16 m net head is almost the same for both CAMs, and the power output of the hydrounit is 17 MW (fig. 13). This power output is obtained in the optimal CAM combination for a guide vane opening S_{ad} = 65.2 % and runner blades inclination S_r.= 37.5 %.

In figure 14 the original CAM combination and the resulted optimum CAM combination are presented, for all three net heads.

For theoretical determination of the optimal operation conditions, the unitary model characteristic of the turbine (fig. 15) is transposed for the analyzed turbine.

The calculus is made for turbine runner diameter of 5 m and the rotational speed of 83.33 rot/min, for a large range of net heads (from 10 m to 24 m, fig. 16), using Moody relation for turbine efficiency

$$\eta_{tb} = 1 - \left(\frac{D_M}{D}\right)^{0.2} + \eta_M \left(\frac{D_M}{D}\right)^{0.2} \left(\frac{n_M}{n}\right)^{0.1} . \quad (4)$$

Considering the net heat 16 m in figure 16, the mechanical power of the turbine at the best efficiency point is 18 MW. This happens for a guide vane opening of a = 39º combined with a runner blades inclination of φ = 19º (fig. 16). For an average value of generator efficiency at 95%, results a power output of the hydro unit of 17.1 MW.

This result is very well correlated with the experimental results from figure 13, where it can be seen that at the best rated efficiency point, the power output is 17 MW.

The runner blades inclination varies 30º and the guide vane opening varies 50º. Considering the best eficiency point of the new CAM characteristic (S_r.= 37.5 % and S_{ad} = 65.2 %), the absolute values are φ = 11.25º for runner blades inclination and a = 32.6º for guide vane opening.

This confirms the optimisation of the new CAM, because the same power output (17 MW) is obtained with a smaller opening of the runner and of the guiding vane, so with a lower discharge.

All these results confirm that in the real operation conditions, with a lower downstream level, the power output of the hydro unit at the best efficiency point is reduced from 22.5 MW (designed value) to 17 MW, for 16 m net head.

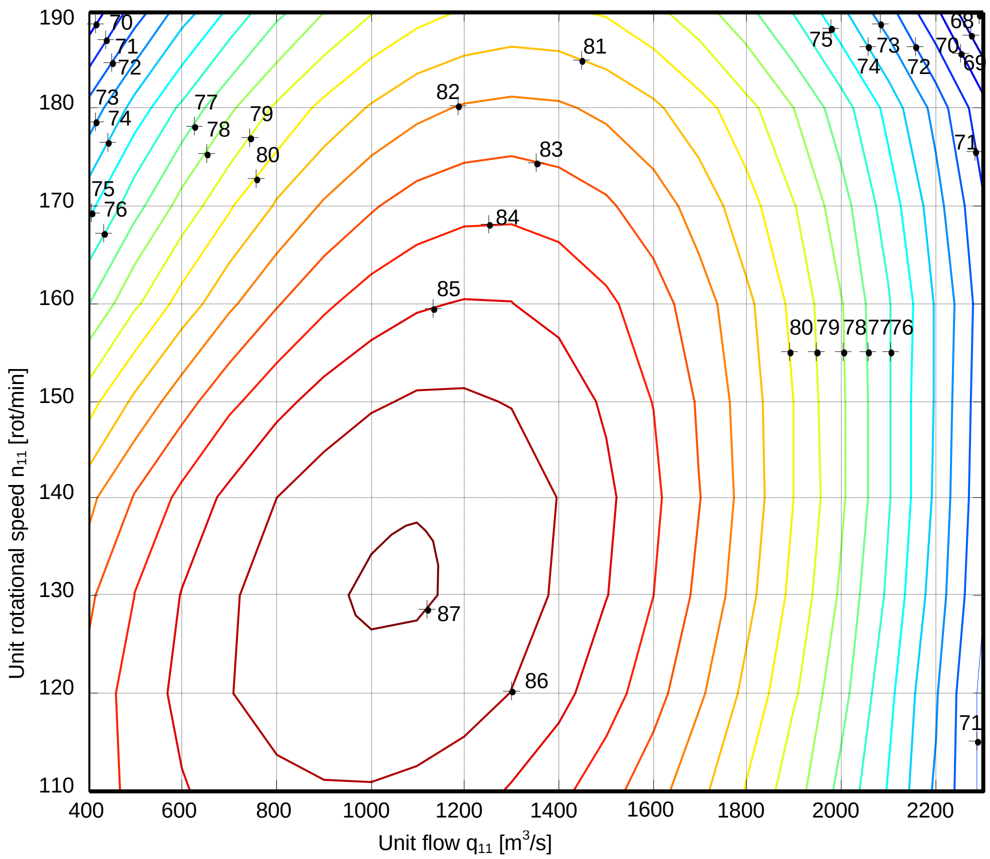

Fig. 15 – Unitary model characteristic of the turbine K20-661

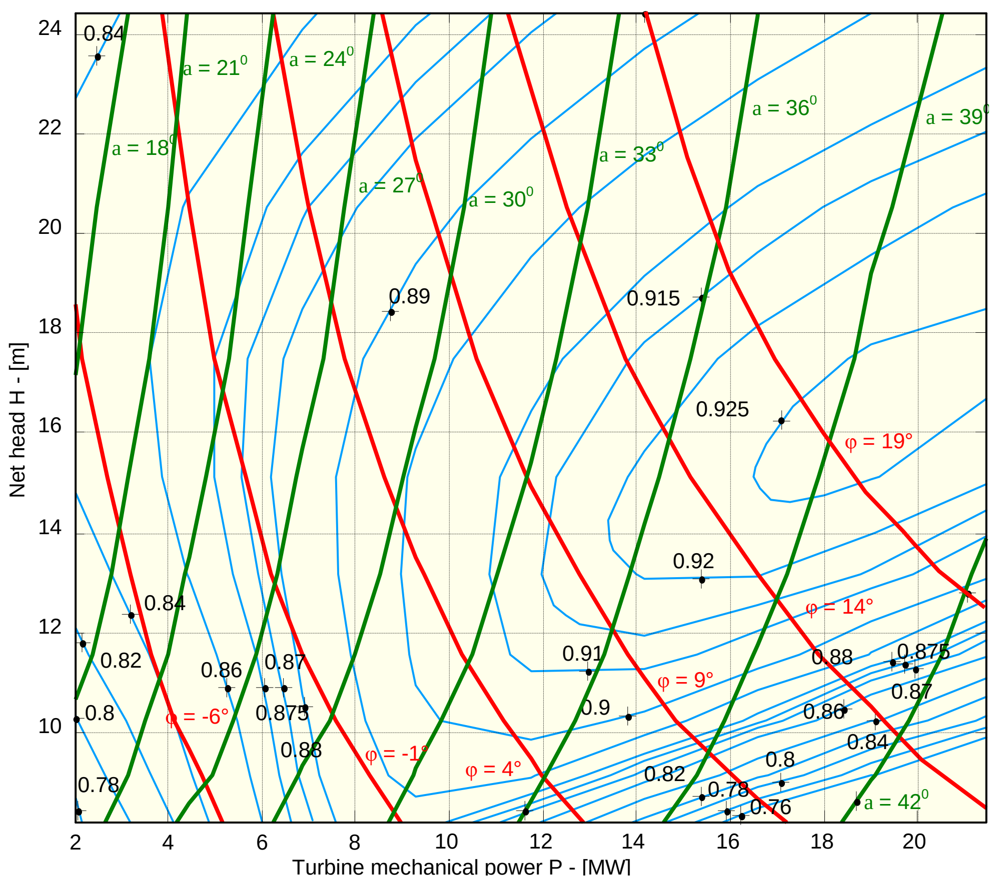

Fig. 16 – Operational characteristic of KVB 22,5-12,5 turbine
(*a* - guide vane opening, φ - runner blades inclination)

5 Vibration analysis

For all measured regimes, the vibrations are also analized. The results are presented for the following power output values of 8 MW, 12 MW, 15 MW and 18 MW at 16 m net head, with the actual and broken-off CAM characteristic.

Machinery vibration characteristics processed in time domain and in frequency domain can be presented on several distinct types of plots. In figures 17, 19, 21, 23 the shaft orbits are presented for four power output values, corresponding to the original CAM combination. In figures 18, 20, 22, 24 are presented the orbits obtained after the CAM relation breaking, close to the optimum regimes.

Theese kinds of plots are useful to identify the shaft preloads. The presence of various types of unidirectional forces acting upon the rotating mechanical system is a normal and expected characteristic of machinery [3].

In figure 25 and 26 the frequency spectrums are presented for the vibration signals acquired on the turbine cover, for power output of 15 MW, close to real best efficiency point. It can be seen that the amplitudes are lower in the operation regime close to the best efficiency point (fig. 25) than in the actual CAM at the same power output (fig. 26).

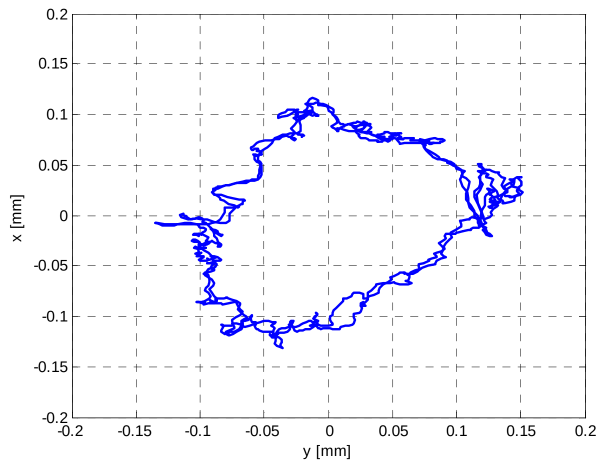

Fig. 17 – Turbine shaft orbit, original CAM characteristic,
8 MW power output

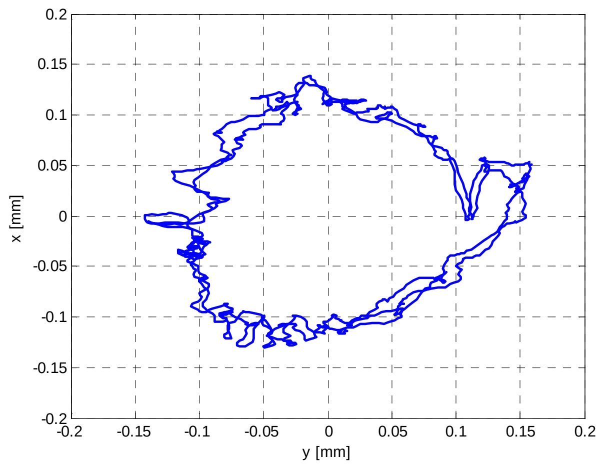

Fig. 18 – Turbine shaft orbit, broken-off CAM approx. 8 MW, S_r = 2.5% and S_{ad} = 45%

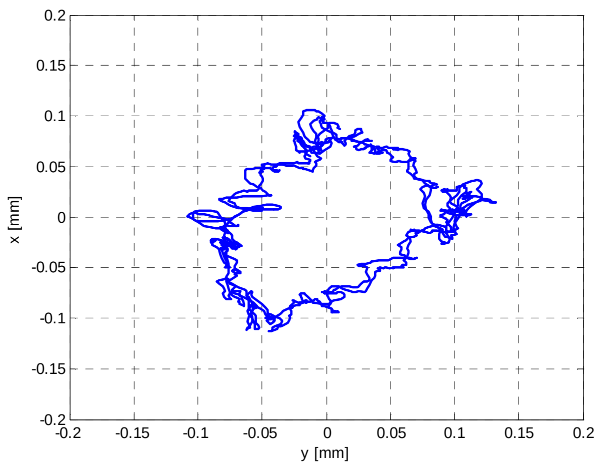

Fig. 19 – Turbine shaft orbit, original CAM characteristic, 12 MW power output

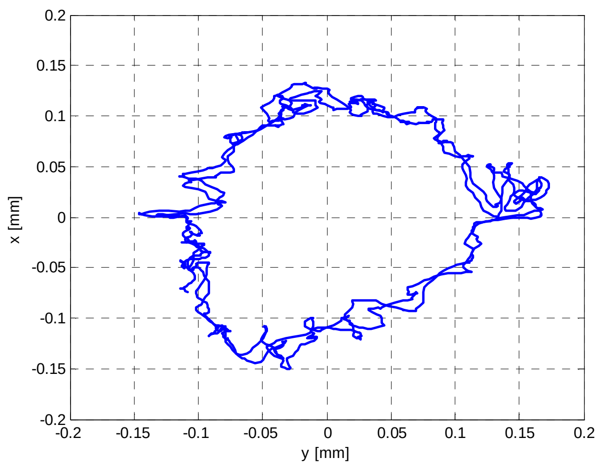

Fig. 20 – Turbine shaft orbit, broken-off CAM approx. 12 MW, S_r = 15% and S_{ad} = 55%

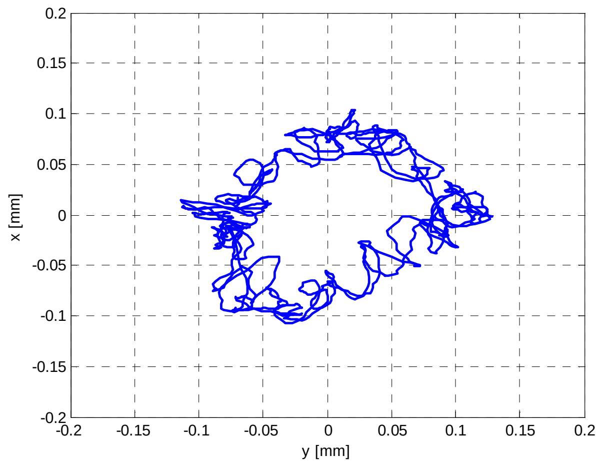

Fig. 21 – Turbine shaft orbit, original CAM characteristic, 15 MW power output

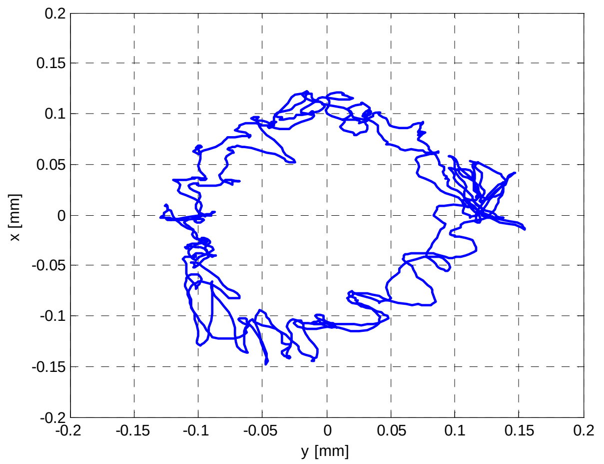

Fig. 22 – Turbine shaft orbit, broken-off CAM approx. 15 MW, S_r = 37.5% and S_{ad} = 64%

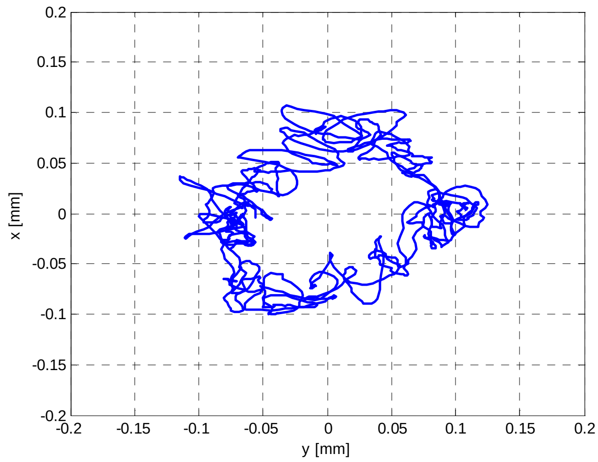

Fig. 23 – Turbine shaft orbit, original CAM characteristic, 18 MW power output

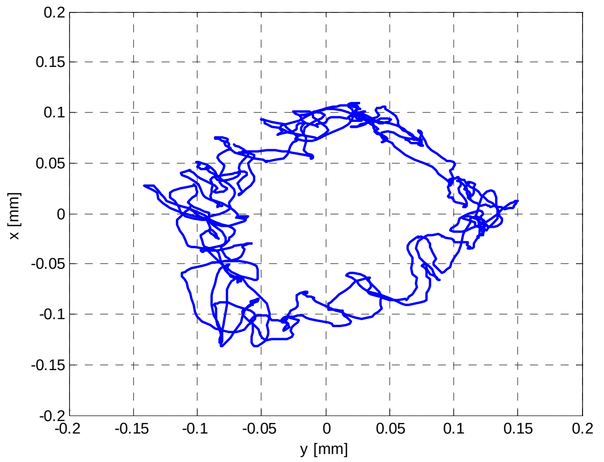

Fig. 24 – Turbine shaft orbit, broken-off CAM approx. 18 MW, S_r = 50% and S_{ad} = 67%

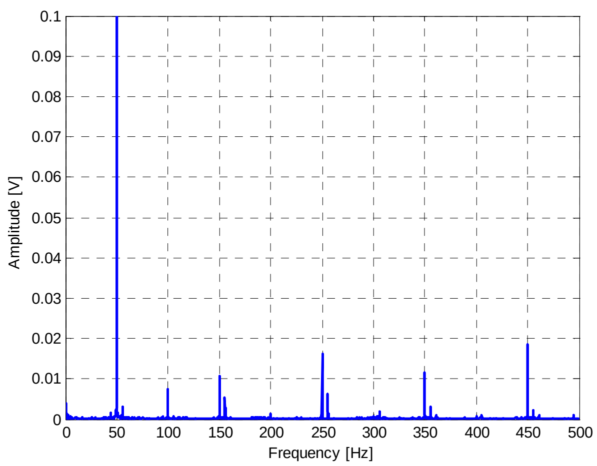

Fig. 25 – FFT plot of the vibration signal on the turbine cover, original CAM characteristic, 15 MW power output

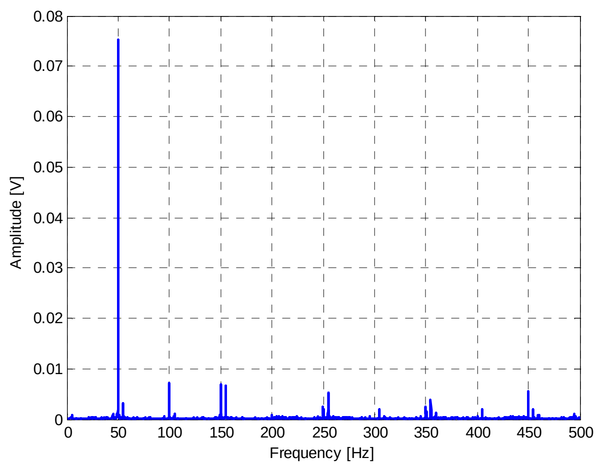

Fig. 26 – FFT plot of the vibration signal on the turbine cover, broken-off CAM approx. 15 MW, S_r = 37.5% and S_{ad} = 64%

6. Conclusions

In this study field tests are performed for a hydro unit which equips a run of river HPP, first in the conditions of the actual CAM, then with the CAM relationship broken off. The efficiency is obtained at different runner blades and guide vanes position combinations across a range of heads.

In the paper the results for one head are presented. The aim is to determine optimal CAM for current conditions of operation (low downstream level) and the hydro unit behavior in operation at various regimes in terms of level of vibration.

After analyzing the measurements results can be stated that the optimum CAM relation obtained by measurements is very different than the actual one. It can be seen that efficiency maximum shifts from a reported discharge of 9 $m^{0.5}$ to 8 $m^{0.5}$. The recommended optimum operation in terms of optimal CAM relation is 6÷8.5 $m^{0.5}$, which corresponds to a electric power of 12÷19 MW.

The shapes of the shaft orbits show a slight preload of the shaft that forces it to have an elliptical motion in all analysed cases. The direction of the orbit displacement is coherent with the direction of the flow entering the turbine impeller. However it can be seen that the shape of the orbits obtained for the original CAM relation are tighter and irregular which indicates that in the new conditions of CAM relation the hydro unit has an improved behavior from the shaft vibration point of view.

Regarding the turbine cover vibrations analysis, it can be seen that their amplitudes are decreased in the best efficiency point comparing to the values measured in the case of the original CAM characteristic.

Acknowledgments

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