Test of Cam Characteristic of the Kaplan Turbine by On-Site Measurement

Aleksandar Gajić
Professor

Faculty of Mechanical Engineering
University of Belgrade

Branislav Ignjatović

HPP Iron Gate,Belgrade

Zvonimir Predić

AP Company, Belgrade

Bojan Ivljanin

Faculty of Mechanical Engineering
University of Belgrade

Unit performance of the river-off hydropower plant that has been in operation for more than 30 *years was to be revised. Despite the fact that the installed Kaplan turbines, with a huge runner diameter of* 9.5 m, *has the highest unit power output of that type in the world, construction of the next stage improved plant cavitation parameters and allowed further increase of the unit discharge and rated unit output respectively. The existing CAM relationship was determined based on hydraulic model tests. The prototype/model length ratio was so high (* $\lambda_L = D_v / D_m \approx 20$ *) and all similarity conditions can not be fulfilled. On the other hand, the CAM combination is dependent on the head, velocity and rotational speed. Because of that, serious field tests were performed, about* 150 *operating regimes carried out with continuous registration of about one hundred physical data: mean pressures and their oscillations, static and dynamic stresses, vibrations, power output, temperatures, etc. Despite big troubles associated with: the flow measurements ranging from* 100 *to* 840 m^3/s *and in huge cross-section areas, the turbine power output measurements through generator output, the variation of the turbine net head due to electricity consumption limitations, etc., high measurement accuracy and repetition of measurement results were obtained. Hydraulic and energy turbine characteristics were tested and unit efficiency determined at the head close to rated one. A good CAM relation was confirmed and power output was increased about* 16%.

Keywords: *Kaplan turbine, measurements, discharge, power output, efficiency*

1. INTRODUCTION

Field tests, as stated in the heading, were carried out on Djerdap I (Iron Gate I) hydropower plant over several past years, [1, 2]. When it was constructed, this hydropower plant had the biggest Kaplan-type turbines in the world, Fig. 1.

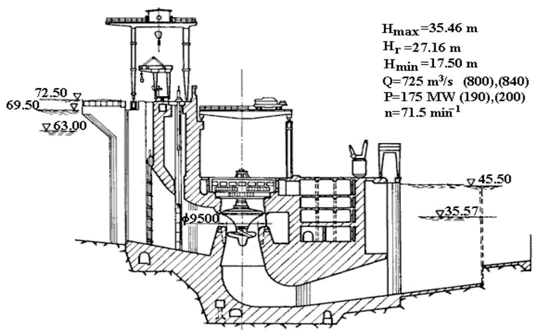

Figure 1. Longitudinal cross-section of the HPP

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Correspondence to: Aleksandar Gajić
Faculty of Mechanical Engineering,
Kraljice Marije 16, 11120 Belgrade 35, Serbia and Montenegro
E-mail: agajic@mas.bg.ac.yu

2. CONDITIONS FOR CAM RELATION TESTS

This time it was certainly possible to test CAM relation for heads corresponding to the present upper and lower water levels and it is close to the rated head.

Prior to turbine manufacture, CAM relation was determined by hydraulic model tests carried out in the laboratory of turbine supplier LMZ 1968/69. Due to a huge turbine size (runner diameter is 9.5 m) and significant discharge capacity, resulting from high specific speed, model dimensions had to be reduced, so that a runner blade model diameter was only 460 mm, head being 3 m. So the length scale ratio was λ_L=20.65. According to thus obtained data, a three-dimensional crankshaft was positioned for adjusting CAM relation, depending on head and required power output.

3. METHOD OF MEASUREMENT

To determine the curves for turbine efficiency (η) dependence of discharge (Q) and a corresponding combination of guide vanes opening (a) and runner blades angle (φ) at the existing head, first a number of operating regimes with a retained CAM relation were registered. The data are graphically presented in Figs 3 and 4.

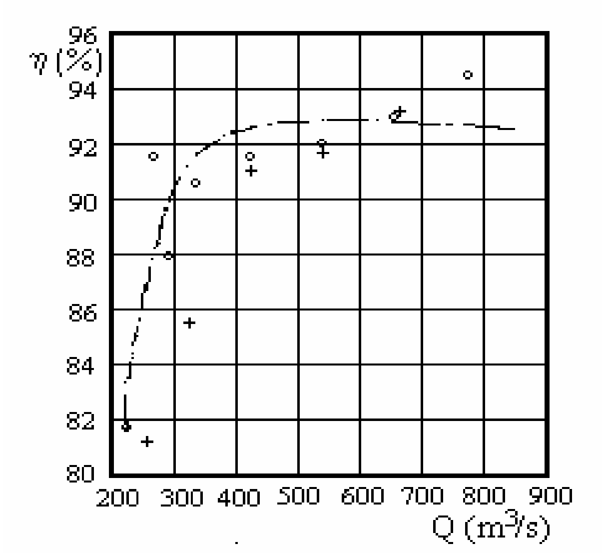

Figure 2. Turbine efficiencies at the existing CAM relation

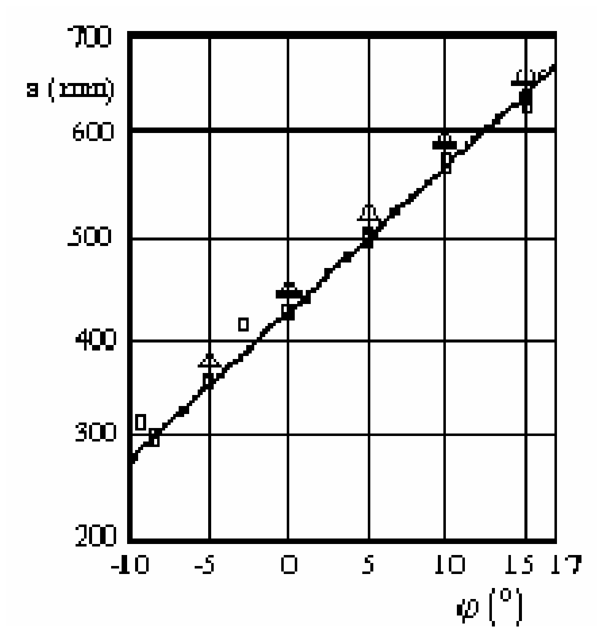

Figure 3. The existing CAM relationship (head at which turbine was tested $H \approx H_R$)

The CAM relation was broken-off at the second stage of tests, and a series of propeller operating regimes with constant runner blade inclinations ($\varphi = -10°, -5°, 0°, 10°, 15°, 17°$) was tested. A number of operating regimes were registered (usually seven) for each inclination φ. On the basis of data analyzed, efficiency curves were drawn, depending on discharge for each φ, i.e. curves $Q-\eta$ for $\varphi = \text{cons.}$, see Fig. 4. By drawing envelope curves around efficiency curves, optimal efficiency values were determined, while vertical lines, drawn through envelope curve contact points with propeller curves to the section with guide vanes inclination change curves for different runner blade angles φ, determine optimal CAM characteristic. A curve was drawn through points thus obtained, defining optimal CAM combination; see lower part in Fig. 4.

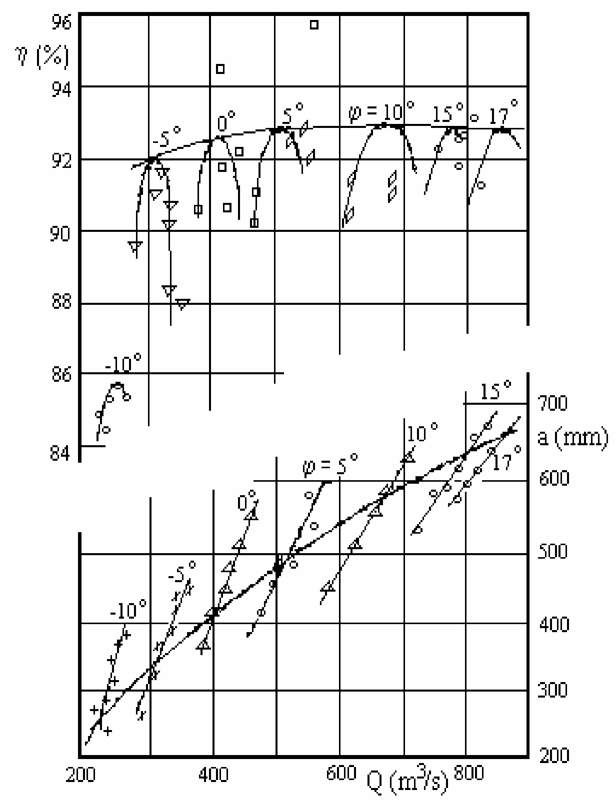

Figure 4. Efficincies at broken-off combination with envelope curve defining optimal values

4. MEASUREMENTS AND DATA PROCESSING

To make the diagrams in Figs 2-4, described in a preceding section, a set of quantities had to be defined and thereafter used for computing the data on discharge, net head, turbine power output and efficiency. All these data had been indirectly defined by measurement of other physical values.

Due to specific conditions, all measurements could not be made according to IEC documents. Of all data, the flow measurements seemed to be the most complicated. Net head and turbine power-output were determined with less difficulty. Data concerning these measured values will be further described.

4.1 Flow measurements

On such a huge plant that has no sections with parallel streamlines, nor has it cross-sections where speed orientations would be known, it was impossible to arrange hydrometric wings to measure local distribution of velocities. Also, it was impossible to apply any other, standard-prescribed, method for flow measurements. This problem was taken into account while plant was being designed, so the plan was to drill holes on spiral casing for pressure taps. Thus, flow measurements were performed by the Winter-Kennedy inertia method. Appropriate taps were also drilled on a model spiral casing and pressure difference dependency on them of the flow were calibrated. The measuring cross-section was at 55° from inlet opening, see Fig. 5.

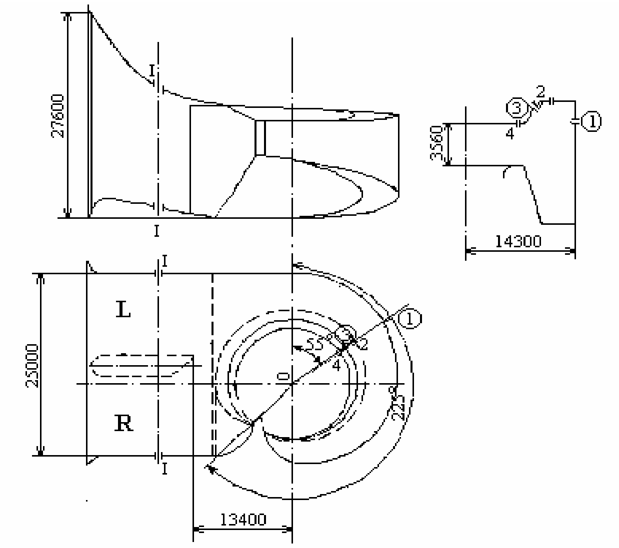

Figure 5. Scheme of a spiral with measuring points

Four taps were drilled: No 1 on the outside and No 2, 3 and 4 on the inside spiral cross-section. Pressure taps of a model as well as those carried out on the plant evidenced that pressure differences between taps 1 and 3 are the most stable, therefore those data were employed in flow calculations by using the expression

$$Q = k \cdot \sqrt{\Delta h_{WK}} \ . \qquad (1)$$

where flow Q is in m^3/s, pressure difference between taps 1 and 3, h_{wk} is in mWC, k is flow constant.

It should be pointed out that it is irrelevant whether coefficient k is accurately determined for the most favorable combination of guide vanes opening and runner blades inclination, because the entire procedure is based on relative flow changes determination. However, successful application requires that the value of coefficient k does not change over the entire flow range. But it turned out that this was not the case in small flows, lower than one-fourth rated, therefore the application of the method is uncertain in that range. Yet, the procedure applied is justifiable, for the plant does not operate when flows are lower than one-third of maximum. Thus, all significant operating regimes are accomplished at constant value of coefficient k, as determined by these measurements.

4.2 Net head

Net head was indirectly determined: by head measurements, being a difference between upper and lower water level, losses at inlet and by computations of kinetic energies on inlet and outlet cross-section. They were determined based on mean flow speeds. In a given case, inlet cross-section is divided by vertical longitudinal wall, Fig. 5, and discharges are not identical through both sections. This is evident from uneven head losses compared to upper water level. In one section head loss is ΔH_L and in the other ΔH_R. Concerning this fact, potential and kinetic energies in inlet cross-section were calculated by weighting these values as proportional to flow squares through parts of inlet cross-section. It was assumed that loss coefficients in both parallel canals were identical. According to these assumptions, net head h is determined by the expression:

$$H = z_1 - z_2 - \frac{\Delta H_L}{1+\sqrt{\Delta H_R / \Delta H_L}} - \frac{\Delta H_R}{1+\sqrt{\Delta H_R / \Delta H_L}} + \frac{2 \cdot Q}{g \cdot A_1^2} \cdot \left[\frac{1}{1+(\Delta H_R / \Delta H_L)^{3/2}} + \frac{1}{1+(\Delta H_L / \Delta H_R)^{3/2}} - \frac{1}{4} \cdot \left(\frac{A_1}{A_2} \right)^2 \right] \qquad (2)$$

In the above expressions z_1 and z_2 are levels of upper and lower water reservoir; Q is turbine discharge in m^3/s, A_1 and A_2 are inlet and outlet cross-section areas in m^2 and g is gravity acceleration in m^2/s.

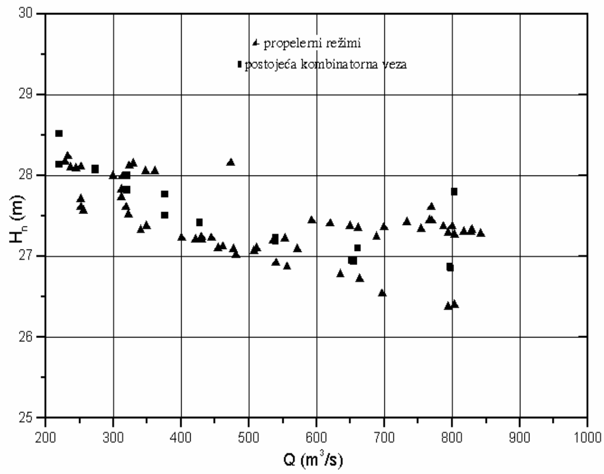

Figure 6. Net heads at the existing and broken off-CAM relationship

4.3 Turbine power output

Turbine power output was also computed by addition of power losses in the generator $\sum P_{Gl}$ and mechanical losses $\sum P_{ml}$ to a measured generator output P_G. The formulas for calculating losses were obtained by generator tests done previously. Losses in generator are divided into losses in copper, iron and excitation. Mechanical losses are in a supporting generator bearing, leading turbine bearing and ventilation losses in the generator. Thus, turbine power output is:

$$P = P_G + \sum P_{Gl} + \sum P_{ml} \qquad (3)$$

Turbine efficiency is determined upon the expression for power output:

$$P_T = \rho \cdot Q \cdot g \cdot h \cdot \eta \qquad (4)$$

where ρ (kg/m^3) is water density, Q (m^3/s) discharge, h (m) net head, η- efficiency, g – gravity acceleration.

5. COMPARISON OF RESULTS

The optimal CAM relationship (a, φ) was determined by indirect measurements of the guide vanes opening (a) and runner blades angle (φ) at tested operating regimes, as presented graphically in Fig. 4.

The tests of existing CAM relation, i.e. for establishing new relations, had been carried out by on-site measurements. Test procedures were described in section 3, and results are presented in Figs 2 and 3.

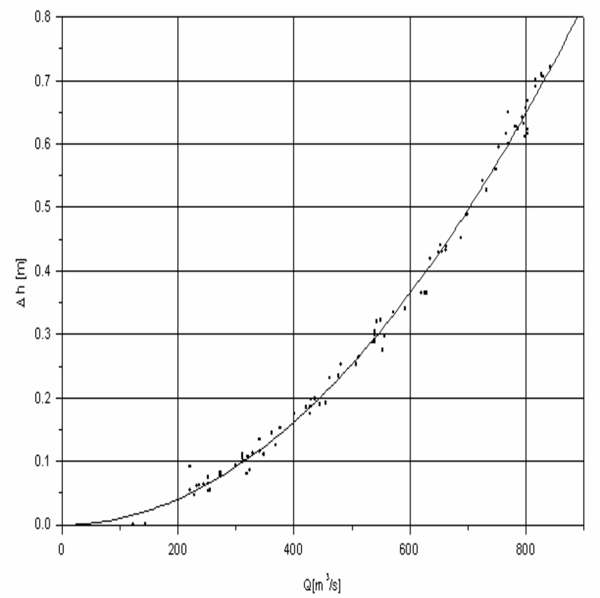

Figure 7. Hydraulic losses of discharge system

To compare both results, reduction to identical heads should be done. That was the reason for comparing net heads at measurements with preserved CAM relation to heads for appropriate flows in tests with broken-off CAM relation. So, satisfactory agreement was found, though both measurements had been made at heads declining with flow increase. Calculations of data to constant net head were neither possible nor justifiable, because the unit had been operating at constant frequency, and the data obtained provide a reliable basis for calculations, concerning relatively small losses.

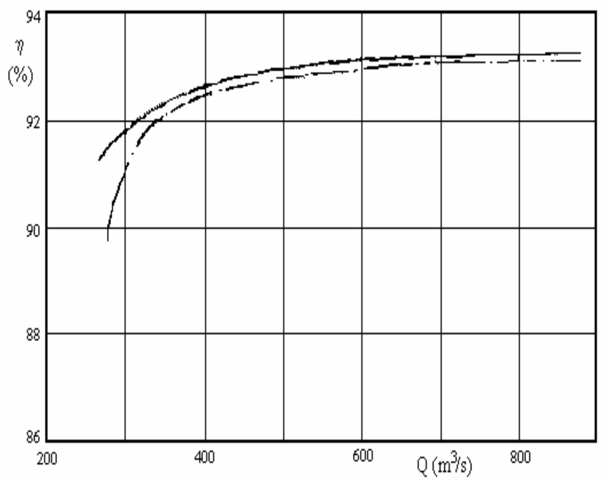

Figure 8. Comparison of efficiency curves in existing and newly established CAM relation

The extraordinary possibility of measurements repetition is illustrated by Fig. 7 which shows dependence of total hydraulic losses Δh (m) on flow Q (m^3/s), thereby the procedure of CAM relation test is fully justifiable.To make comparison easier, Fig. 8 shows both efficiency curves, obtained in the existing CAM relation or looked for in broken-off relationship. In Fig. 9 CAM characteristics from Fig. 4 was drawn in again, and points corresponding optimal CAM relation, as determined in Fig. 3, were drawn in too. The agreement was so high that two lines could not be drawn.

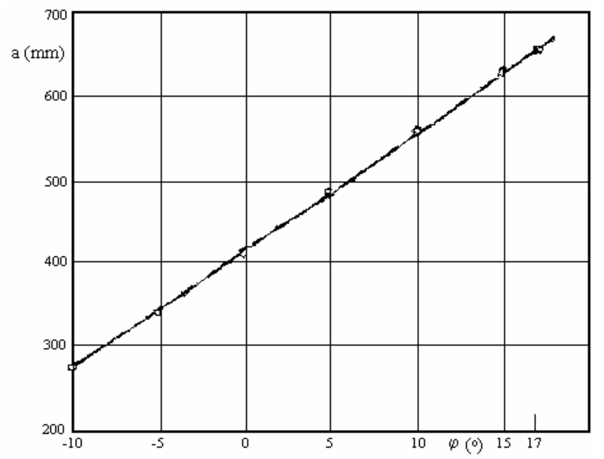

Figure 9. Comparison between optimum and existing CAM relation

6. CONCLUSION

A remarkable agreement is evident from efficiency curves, Fig. 4., except in the range of discharge below 350 m^3/s, and it is the range where Winter-Kennedy methods provide uncertain data. Minimum difference in efficiencies for flows beyond 350 m^3/s to the highest ones is primarily conditioned by measurement errors. And yet, it should be born in mind that such agreement justifies the application of a relative method, therefore the obtained efficiency values should be taken like that.

However, the ideal agreement of data on optimal CAM characteristic confirmed by model and on site measurements, Fig. 9, the ultimate conclusion can not be drawn. We could conclude that it is necessary to change or correct the existing combination based on measurements at a number of different head values, including the highest and lowest ones. This certainly requires a longer period of time, may be longer than a year.

The said conclusion suggests another one, and it is concerning mutual positions of turbines. It is beyond dispute that water inflow and, to an extent, discharge conditions are slightly different for each of them. Also, the effect of power output distribution should not be neglected, when inflows to adjacent units are different. To explore these phenomena more extensively, measurements should be made on all units, or at least on three i.e. on two outermost and on one in the middle. It seems that these measurements should not comprise all heads.

It was not only that good CAM characteristic was confirmed, but also characteristics were determined at power outputs and flows far beyond boundary quantities as defined by a primary contract. To draw the final conclusion, it is necessary to consider other aspects of unit safety, reliability of hydro mechanical equipment, control characteristics and technical resources of the whole plant.

ACKNOWLEDGEMENT

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ПРОВЕРА КОМБИНАТОРНЕ ВЕЗЕ КАПЛАН ТУРБИНЕ МЕРЕЊЕМ НА ТЕРЕНУ

Александар Гајић, Бранислав Игњатовић, Звонимир Предић, Бојан Ивљанин

Комбинаторна зависност Капланове турбине, која је у погону више од 30 година, утврђена је на основу моделских испитивања. У циљу ревитали-зације хидроелектране и утврђивања потребних захвата, извршена су детаљна испитивања енергетских карактеристика мерењем на терену.

Испитано је преко 150 радних режима при паду у околини номиналног. Посебно су истакнуте тешкоће настале због великог опсега протока, од 100 до 840 m^3/s, и несиметричног дотока воде.