CAM CURVE IN KAPLAN TURBINE, A SENSITIVITY ANALYSIS

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An experiment was designed based on the design of experiment method to evaluate the uncertainty in Kaplan CAM curve determination. The variation is negligible around the best efficiency point, below the estimated measurement error. The variations in efficiency are at their largest before the propeller top and may vary between a high efficiency and significantly lower efficiency at this point. Additional measurements are recommended to capture such behaviour.

There was no clear indication of a hysteresis in the runner blade or guide vanes mechanism. However, a constant difference in the readings between the fixed scale and the station sensor was observed.

Keywords: Kaplan, CAM curve, design of experiments.

1. Introduction

Kaplan turbines are low head hydraulic turbines doubly regulated. The cam curve determines the relation between the guide vane angle and runner blade angle for an optimum efficiency independently of the flow rate. Relative efficiency measurements using the Winter-Kennedy method for relative flow determination are a popular method for determining Kaplan turbine cam curves. They are usually performed with about 5 guide vane angles for a given blade runner angle. Such measurements are performed during the commissioning and at regular time interval of about 10 years. Substantial deviations from the optimum cam curve may sometimes be found, which origin are not easy to sort out. Any deviation from the optimum cam curve results in an economic loss for the turbine owner.

A solution to this kind of deviation may be a continuous monitoring and optimization of the came curve, i.e., the cam curve will continuously be estimated function of the operational conditions of the machine; head and flow rate. Such continuous relative efficiency measurements may be coupled to an absolute flow measurements system such as the pressure-time method allowing a continuous

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efficiency measurement. This principle is not new and was recently re-examined by Nicolle & Proulx [1]. The inner pressure tap was situated closer to the guide vane. An ultrasonic device was used to determine the absolute value of the flow rate and adjust the Winter-Kennedy constant.

The feasibility and usefulness of the method are clear, but there is still some basic question related to the method itself. The random uncertainty in the measurements is usually not handled during a relative efficiency and cam curve determination. Furthermore, the torque acting on the guide vanes and runner blades varies function of the angle, which may lead to some hysteresis phenomenon.

In order to answer these basic questions, experiments were performed on a full scale Kaplan machine of 100 MW with focus on the behavior of the guide vane and runner blade angles. A standard relative efficiency measurements and cam curve determination were performed followed by an extensive experiment base on the design of experiment method. Measurements were performed in a random order for two propeller curves with eight replicates. Ten different guide vane angles were used, five for each runner blade angle. A total of 80 measurements were performed over the span of two days. The measurements were compared with the results from the relative efficiency test performed the day before on the same full-scale machine.

2. Material and methods

The experiment was performed on a full-scale hydropower turbine situated on the Luleå River, Sweden. The turbine is a Kaplan of 100 MW. The rated head and flow rate of the turbine are 32.5 m and 350 m^3/s. The turbine runner diameter is 6.8 m, with a rotational speed of 115 rpm.

The measurement equipment consisted of a data acquisition system using the software Lab View. Power meter with an accuracy of 0,1% and submersible pressure transducer to measure head and tail water levels were used.

The sampling frequency was 2500 Hz during the test; each 250^{th} sample was registered and saved in a log file. In order to have stable measuring values a low pas filer of 0.500 Hz was used.

The data acquisition system was connected to the plant/unit governing system to register the stations reading of the generator power, head and tail water level, generator current, generator voltage, runner blade angle and guide vane opening.

The signal (4 – 20 mA) for the guide vane opening, runner blade angle, head water level and tail water level where connected to the data acquisition system. In parallel to the registration of the turbine signals, visual reading on the mechanical scales was performed. For the guide vane opening two scales were used, one showed the guide vane angle and the other showed the stroke of the servomotor. The runner blade angle scale showed the blade opening from -15 degrees to +15 degrees.

The measurement equipment was connected and controlled according to standard procedures during index tests. The same equipment and placement of the sensors was used during both the experiment and the relative efficiency measurements. Before the measurements, the sensors were calibrated and readings were cross-checked with other sensors and known inputs according to standard procedures. Ten minutes measurement on the differential pressure sensor was used to determine the accumulated flow rate function of time. A measurements time of 4 minutes was found enough get variation below 0.1%. The same period of 4 minutes was used to settle the flow after the movement of the guide vanes and runner blades.

The experiment consisted of 80 measurements with 10 different settings varying a random manner according to a pre-planned schedule. The 10 different settings consisted of two runner blade angles and 5 guide vane angles. The runner blade angles were chosen to be similar to two of the blade angles investigated the day before during the standard measurements; near the best efficiency point and at a higher load. A guide vane angle on the top of the propeller curve and two angles on each side of the propeller curve were chosen.

The design of experiment method was utilized to design the experiment. For cases with multiple parameters, a factorial design is recommended for capturing interaction between parameters [2]. In the present work, a full factorial experiment was chosen.

Two parameters were chosen for the experiment; the guide vane angle and the runner blade angle. The guide vane and runner blade direction movement and potential difference related to this movement were not used as parameter in the planning because the number of measurement will increase significantly and thus the experimental time.

The measurement program was created using a random number generator in MS Excel. All statistical data were derived using the MS Excel Add-In Analysis Toolpak to generate Analysis Of Variance tables; ANOVA tables.

For index testing, a significance of 95 % is necessary [3].To determine the necessary number of samples and repetitions to achieve a statistical significance of 95 %, the following considerations are necessary.

The significance of a test relates to two types of error; type I error and type II error. Type I error (α) is the probability that two sample populations are assumed to have unequal mean values but have equal mean values. The type II error (β) is when two sample populations are assumed to have equal mean values but have different mean values. Typically a test is designed to have an α-value of 0.05, corresponding to a 95 % significance. The number of samples is then determined in order to have a β-value of 0.05 or smaller, meaning a significance of 95 % or higher [2].

The number of replicates (n) to achieve a maximum β-value of 0.05 was calculated by assuming equal sample variance (σ^2) and equal sample population size. Then the required number of samples could be calculated according to equation (1) for the runner blade angle.

$$\Phi^2 = \frac{nbD^2}{2\alpha\sigma^2} \tag{1}$$

In equation (1), (b) is the number of levels for factor B. The sample variance (σ^2) is calculated according to equation (3). (D) is the difference in treatments, i.e., between two treatments. (D) is calculated from equation (2) using the two population means. Φ^2 can be read from operating characteristic curves for the fixed effects model of variance with assumed probability for type I error of 0.05 [2], then the corresponding β-value is obtained from the reference.

$$\mathrm{D} = |\mu_1 - \mu_2| \tag{2}$$

μ_1 and μ_2 are the mean values of the factor investigated.
For the guide vanes, another method was used, approximating increase or decrease of the guide vanes angle as two different levels of a single variable. A single variable with two levels was assumed to obtain the operating characteristic curves for the two-sided t-test with $\alpha = 0.05$ [2]. The probability for the β error is obtained from the reference [2]. The number of replicates for a specified difference of the mean values can be obtained from these two conditions. This method also assumes equal variance and equal population sample size.

When several aspects are simultaneously investigated, the necessary amount of samples for each aspect under investigation needs to be calculated separately if they have different means and/or variance. If the sample variances were to differ, the following equation has been used to calculate the average estimated standard deviation

$$\overline{\sigma} = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{3}$$

The relative efficiency was calculated with the following equations;

$$\eta_{rel} = \frac{N_t}{(Q_{rel} \cdot H \cdot \rho \cdot g)} \tag{4}$$

$$H_{gross} = z_{hw} - z_{tw} + \frac{v_0^2}{2g} - \frac{v_{tw}^2}{2g} \tag{5}$$

$$N_t = P_{gen} + P_{gen-f} \tag{6}$$

$$P_{gen-f} = P_{tom} + P_{tom-mag} + \left(P_{bel} + P_{bel-mag}\right) \cdot (I/I_m)^2 \tag{7}$$

$$Q = k \cdot (\Delta P)^n \tag{8}$$

Assuming efficiency ratio at different heads equal to 1, the results were normalized to a single head using the similarity relation below (9)

$$Q_1/Q_2 = (D_1/D_2)^2 \cdot \sqrt{H_1}/\sqrt{H_2} \cdot \sqrt{\eta_1}/\sqrt{\eta_2} \tag{9}$$

3. Results

The variation of the guide vanes angle is presented for both sensors in figure 1: the station sensor and the fixed scale sensor. Values for increasing and decreasing adjustment of the guide vanes are presented. A straight line is expected for such comparison with an eventual systematic bias. The results are clearly different with some variation approaching 1.5°. The deviation decreases when focus on one sort of adjustment.

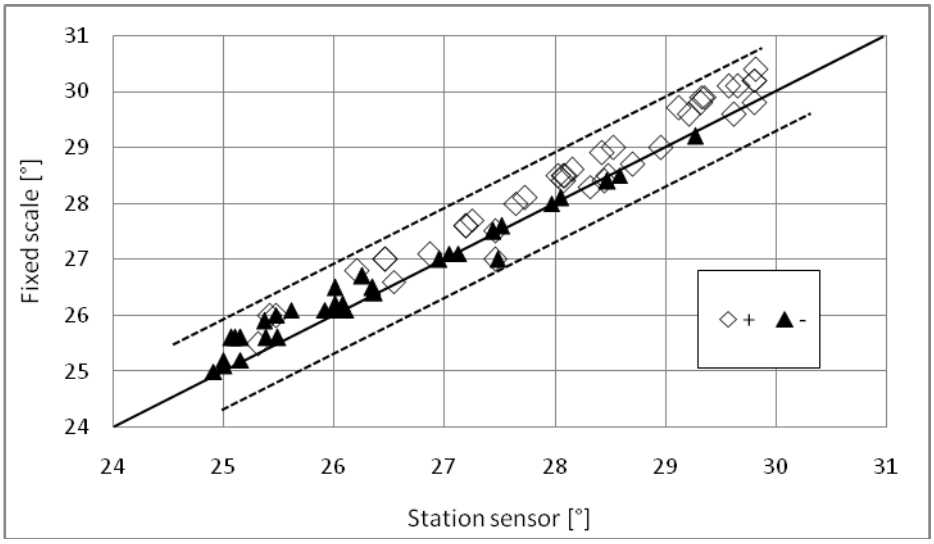

Fig. 1. Variation of the guide vanes angle for the station sensor and the fixed scale sensor, presented for an ascending and descending adjustment for all measurements performed (BEP, HL).

Figure 2 presents the variation of the guide vanes angle for the station sensor and the fixed scale sensor function of the square root of the differential pressure, i.e., the flow rate. The random behaviour of the station sensor is larger.

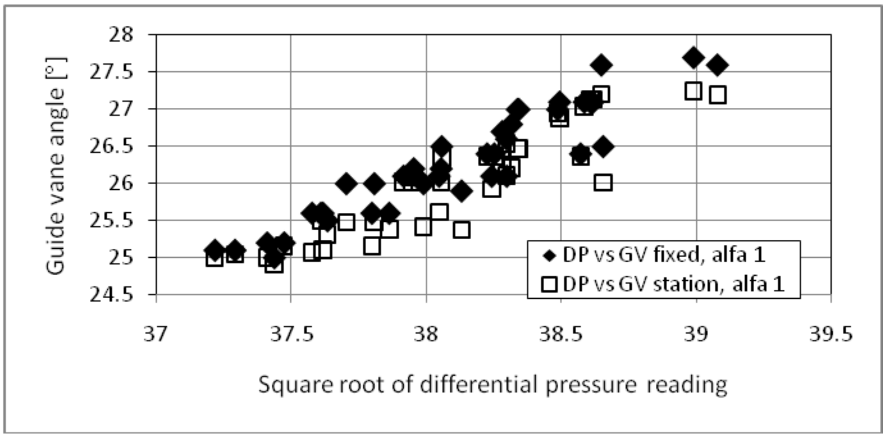

Fig. 2. Variation of the guide vanes angle for the station sensor function of the square root of the differential pressure, i.e., the flow rate at the best efficiency point (BEP).

The station sensor is used during operation of the turbine and is thus used in the following. Figure 3 and 4 present the variation of the efficiency function of the flow rate at the best efficiency point (BEP) and at high load (HL). Both the standard efficiency measurements and design of experiment are presented. The large number of replicate in the design of experiment allows calculating a standard deviation presented in the figures. The efficiency is normalized.

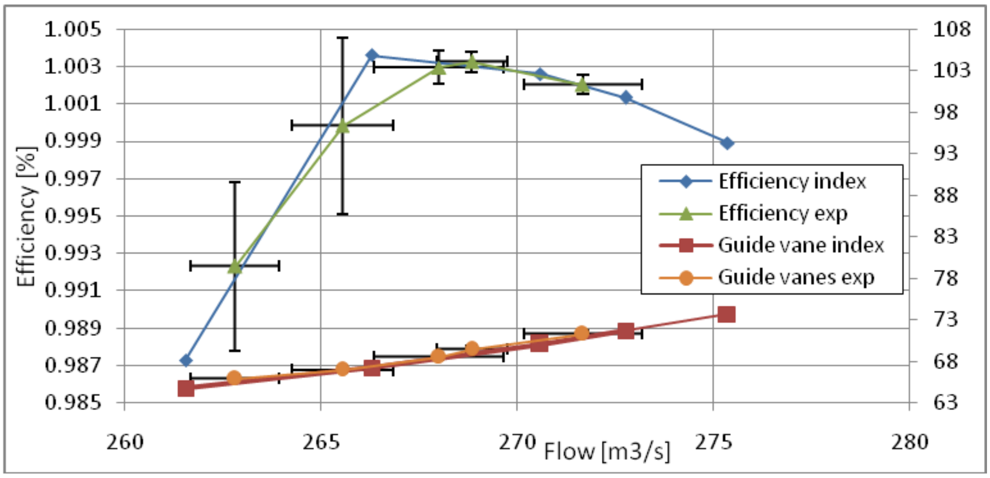

Fig. 3. Efficiency function of the flow rate at the best efficiency point (BEP) for the standard efficiency measurements and the design of experiments. Error bars represent the standard deviation. The percentage of the guide vanes opening (left vertical axis) function of the flow rate is also presented for both measurements.

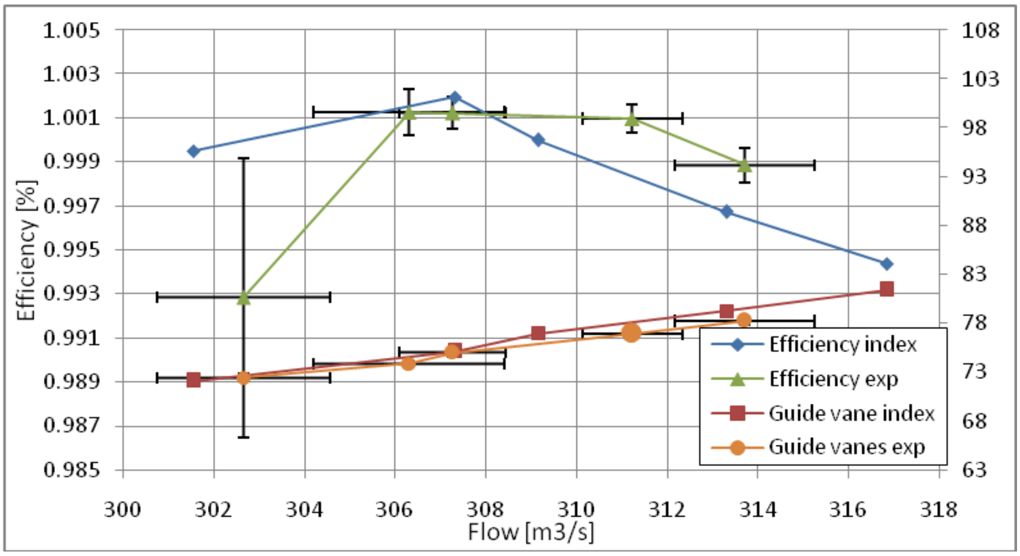

Fig. 4. Efficiency function of the flow rate at high load (HL) for the standard efficiency measurements and the design of experiments. Error bars represent the standard deviation. The percentage of the guide vanes opening (left vertical axis) function of the flow rate is also presented for both measurements.

The variation in the efficiency is small for repeated samples; the largest interval is 1%. At BEP, the standard measurements (efficiency index) are well inside the interval defined by the standard deviation. At HL, deviation appears, both on the left and right of the propeller curve; the reason is unclear.

6. Conclusions

An experiment was designed based on the design of experiment method to evaluate the uncertainty in Kaplan CAM curve determination. Overall, the uncertainty is the CAM curve determination is small. The variation is negligible around the best efficiency point, below the estimated measurement error. The variations in efficiency are at their largest before the propeller top and may vary between a high efficiency and significantly lower efficiency at this point. Additional measurements are recommended to capture such behavior.

NOMENCLATURE

Number of replicates	n	-
Number of levels for factor A	a	-
Number of levels for factor B	b	
Absolute difference between two sample means (two-factor	D	-

factorial)		
Variable used for estimating risk for β error in a two-sided t-test	d	-
Mean standard deviation	σ	-
Variable used for estimating risk for β error in a fixed effects model	Φ^2	-
The power removed from the water by the turbine	N_t	[W]
Head	H	[m]
Gravity acceleration	g	[m/s^2]
Density of water	ρ	[kg/m^3]
Flow rate	Q	[m^3/s]
Efficiency	η	-
Headwater level	z_{hw}	[masl]
Tailwater level	z_{tw}	[masl]
Velocity at a point i in the turbine waterways	v_i	[m/s]
Generator power	P_{gen}	[W]
Generator losses	P_{gen-f}	[W]
no load losses	P_{tom}	[W]
Generator load losses	P_{bel}	[W]
Generator current	I	[A]
Designed generator current	I_m	[A]
Magnetic no load losses	$P_{tom-mag}$	[W]
Magnetic losses depending on load	$P_{bel-mag}$	[W]
Flow coefficient	k	[m$^{7/2}$/kg$^{1/2}$]
Differential pressure	ΔP	[Pa]
Pressure exponent	n	-
Turbine (Runner) diameter, if same turbine equal to 1	D_1, D_2	[m]
Type I error	α	-
Type II error	β	-

R E F E R E N C E S

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