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Experimental investigation of a Kaplan draft tube – Part II: Off-design conditions

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ABSTRACT

Off-design conditions of hydropower turbines are becoming more frequent with the deregulation of electricity markets and the introduction of renewable energy resources. Originally, turbines were not built to operate under such conditions. It is evident that there is a need to develop turbines that can operate under off-design conditions while attaining high efficiency. This may be achieved with computational fluid dynamics (CFD). However, the complexity of Kaplan turbine flows is challenging to treat using CFD. Therefore, detailed experimental investigations are necessary to validate and develop CFD.

This paper presents an investigation of a modern design Kaplan turbine model. The measurements were performed in the draft tube with laser Doppler anemometry and flush-mounted pressure sensors, with a focus on the part load and high load operation of the turbine. Mean and phase-averaged quantities are presented for the velocity and pressure along several sections. A contra-rotating flow region was observed under high load operation. Under part load operation, a rotating vortex rope (RVR) develops due to vortex breakdown. The presence of the RVR significantly reduces the draft tube performance.

1. Introduction

Part load operations as well as start/stop of the turbines are becoming more frequent with the deregulation of electricity markets and the introduction of renewable energy resources. Doubly regulated reaction turbines of the Kaplan type are the best adapted for such a scheme because they offer a wide operating range with relatively high efficiency. Nevertheless, they are not designed to operate under unfavorable flow conditions. Away from the best efficiency region, vibrations increase, leading to wear and eventually failure. There is a need to develop turbines that can operate outside the best efficiency region. This may be achieved with the help of computational fluid dynamics (CFD). However, the complexity of Kaplan flows is challenging to treat using CFD. Detailed experimental investigations are necessary to validate and develop CFD.

The available literature on detailed experimental investigations of Kaplan turbines is limited. Andersson [1] and Lövgren [2] investigated in detail the flow in a Kaplan draft tube, whose design dated from the 1950s, near the best efficiency point (BEP). More recently, the research group at Laval University, Canada investigated a propeller turbine model at design and off-design operational points [3]. The results were used to validate CFD and develop an understanding of the turbine behavior under off-design conditions. There is an evident need for the investigation of turbines under part load and high load operations to better predict transient turbine behavior.

This paper is the second of two consecutive papers reporting the experimental investigation of a modern Kaplan turbine design known as U9. The investigation was performed at three working points with a constant blade angle: the part load point, BEP and the high load point. Paper I [4] dealt with a presentation of materials, methods and results related to the BEP. The present paper concentrates on the results for the part load and high load points.

2. Experimental apparatus and procedures

The investigation was performed using a 1:3.1 scale model of the U9 Kaplan turbine. The prototype turbine is situated in the Lule River in northern Sweden. The U9 prototype operates under a head of 55 m and produces 10 MW at maximum discharge ($Q = 20$ m^3/s). It consists of a spiral casing, 6 runner blades and an elbow draft tube. The prototype unit was built solely for research, developmental and educational purposes.

The studied model has a runner diameter of 0.5 m. The head was set to $H = 7.5$ m and the runner speed to $N = 696.3$ rpm. The present paper reports measurements of the turbine under off-design conditions: under part load operation and near the maximum discharge. For both loads, the runner blade angle was held constant and equal to that for BEP, i.e., the turbine was operated in off-cam mode. The guide vane angle was 20° and 32° for the part load and high load, respectively. An overview of the operational parameters is provided in Table 1.

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Nomenclature

α	phase, s
Φ	instantaneous quantity
$\overline{\Phi}$	time-averaged quantity
$\tilde{\Phi}$	periodic fluctuation quantity
Φ'	random fluctuation quantity
Φ_M	quantity expressed as Fourier series of M harmonics
δ	relative exit flow angle, rad
ϵ	estimated value mean value
γ_i	flow angle, rad
θ	phase angle, rad
A	cross-sectional area, m^2
a_0, a_m, b_m	Fourier coefficients
c	peripheral velocity, m/s
Cp_w	pressure recovery coefficient based on the wall pressure
Cp_{ideal}	ideal pressure recovery coefficient
f^*	normalized frequency (f/f_n)
f_n	runner frequency (11.59 Hz), Hz
H	head of the turbine, m
L^*	normalized length (by R)
M	number of harmonics
N	runner speed, rpm
P	pressure, Pa
Q	discharge, m^3/s
R	runner radius, m
r^*	normalized radius (r/R)
r_{RVR}	precession radius, m
Sw	swirl intensity
U, V	axial and tangential velocity, m/s
U^*, V^*	normalized velocities (U/U_T,V/U_T), m/s
u^{*2}, v^{*2}, uv^*	normalized Reynolds stress components $\left(u^2/U_T^2, v^2/U_T^2, uv/U_T^2\right)$. For part load, u^{*2}, v^{*2} and uv^* correspond to combined fluctuations due to turbulence, and the random movement and shape variations of the RVR
u^*, v^*	normalized RMS (u/U_T, v/U_T)
u_i, v_i, w_i	vertical, absolute and relative velocity, m/s
U_T	bulk velocity, m/s
BEP	best efficiency point
LDA	laser Doppler anemometry
RVR	rotating vortex rope

The measurements were performed at the Vattenfall Research and Development model test facility in Älvkarleby, Sweden. The test rig used for the measurements is a closed-loop system, and the turbine was placed between two pressurized tanks. The pressure difference between the two tanks was adjusted to the desired head, and the absolute pressure of the two tanks was set high enough to avoid cavitation. For all measurements, a magnetic encoder was used to capture each runner revolution for phase analysis. Further details of the test rig and its layout are found in Part I [4].

2.1. Velocity measurements

A two-component laser Doppler anemometer (LDA) with an 85-mm optical fiber probe from Dantec was used to measure the velocity. The probe uses a backscatter configuration. A front lens with a 600-mm focal length was used. The basic configuration of the system consisted of continuous wave 20-W argon-ion laser and transmitting optics, including a beam splitter Bragg-cell, photodetector and signal processor. The measuring volume size was estimated to be 2.229 × 0.140 mm for the axial velocity component and 2.426 × 0.147 mm for the tangential velocity component. The burst mode of spectral analysis method was used during data acquisition. The total sampling time was set to 300 s for each measurement point. This corresponded to 20,000–300,000 bursts for each measurement point, which were a function of the location of the measuring points. The velocity measurements were made in coincidence mode. Seeding particles made of polyamide powder with an average diameter of 5 μm were used. Measurements were performed at four windows with angular positions a, b, c and d, with 90° spacing, around the cone circumference (Fig. 1b). Three locations along the vertical direction were investigated at each angular position: Sections I–III (Fig. 1a). For further details, see Part I [4] and Mulu and Cervantes [5].

Table 1
Operational parameters.

Operating point	Part load	High load
Guide vane angle (°)	20	32
Discharge (m^3/s)	0.62	0.76
Unit discharge (–)	0.9	1.1

2.2. Pressure measurements

The pressure measurements were performed in the draft tube cone and elbow: 20 positions in the cone and 13 in the elbow. A reference sensor was placed on the upper part of the draft tube, near the outlet. Fig. 1 shows the measurement locations in the draft tube. The pressure taps in the cone were placed at four angular locations around the cone circumference (a–d), with five taps equally spaced in the vertical direction (1–5). Six and seven pressure taps were placed on the outer and inner radius of the elbow, respectively. However, due to a welded joint the taps on the inner radius were placed 25 mm in the counterclockwise direction from position c.

Membrane-type pressure transducers from Druck (PDCR810) with an accuracy of 0.1% were used for the pressure measurements. The transducers were randomly switched between the pressure taps to cover all positions twice. For all measurements, the pressure at the reference position was simultaneous measured. Two sampling frequencies were used: 5 and 2 kHz, with a sampling time of 120 and 240 s, respectively. The former was used to accurately phase-resolve the data at the runner frequency. The latter was used for time-averaging and RVR phase analysis; thus, longer time series produce a more accurate mean value and capture more RVR periods for the phase-average. For further details regarding the measurement procedure, see Part I [4] and Jonsson and Cervantes [6].

2.3. Data processing

A time-dependent turbulent flow was created at the draft tube inlet due to the runner rotation. The frequencies were related to the runner frequency and its synchronous frequencies, such as the blade passage frequency. At part load, a precessing helical vortex rope developed due to vortex breakdown. In hydropower applications, this phenomenon is usually referred to as an RVR