

Experimental Determination of Cavitation Characteristics of Hydraulic Turbines

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Abstract— A new facility for the design, manufacturing and standardized tests of model hydraulic turbines is under construction at TOBB University of Economics and Technology. The facility is one of a few of its kind, in the sense that, it involves the whole process of hydraulic turbine design, including computational fluid dynamics (CFD) aided hydraulic and mechanical design, manufacturing and standardized performance tests. This work summarizes the capabilities of the "Center for Hydro Energy Research (ETU Hydro)" at the university and focuses on the cavitation tests of the model turbines. The cavitation characteristics of the turbines are determined with the help of several tests that meet the required standards, the details of which are given in this paper.

Index Terms— Cavitation, Experiment, Francis Turbine, Test stand, Similitude

I. INTRODUCTION

Hydroturbines are one of the two main components of Hydroelectric power plants (HEPPs). (The other one is the generator). HEPPs are used to convert the energy of water into electricity. Compared to other types of energy generation, they are considered renewable and they still have potential.

Experimental and numerical techniques are widely used in the design of hydraulic turbines. Although the numerical methods and the computational fluid dynamics (CFD) techniques used today are improved, experiments are still necessary to determine efficiency at specified head and discharge values, pressure differences and especially cavitation characteristics. Hydraulic laboratories in accordance with the standards of the International

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Electrotechnical Commission (IEC) are established to perform the related experiments.

Most of the laboratories belong to companies that manufacture hydraulic turbines such as Rainpower (Norway) [4], Global Scale Model Test Laboratory (ALSTOM Hydro) in France [5], VATECH [6], VOITH-Siemens [7], and Fine Institute [8]. There are also several university based hydroturbine test centers such as Laboratory for Hydraulic Machinery of EPFL in Switzerland [9] and Turboinstitut in Slovakia [10].

The capacity of Fine Institute of Hydraulic Machinery is given in Table 1. This laboratory consists of three test rigs which can be used for the tests of Francis type turbines, reversible pump-turbines, Kaplan and Bulb turbines. The hydraulic turbine characteristics such as efficiency, runaway speed, cavitation characteristics and pressure fluctuations are determined [8].

TABLE I
CAPACITY OF FINE INSTITUTE OF HYDROMACHINERY TEST RIGS [8]

	Francis Type Turbines	Kaplan& Bulb Type Turbines
Maximum Head (m)	90	40
Maximum Flow Rate (m³/s)	1.2	1.8
Pump Capacity (kW)	750	750
Maximum speed of Motor/generator (r/min)	3000	3000

The capacity of S. Morgan Smith Memorial Hydraulic Laboratory (Voith) [7], is 131 m head, 1.13 m³/s flow rate. The laboratory for Hydraulic Machinery of EPFL [9] can operate up to a maximum head value of 100 m and maximum discharge rate of 1.4 m³/s.

In hydroturbine test centers, there are two main test circuits. First one is the performance circuit at which the tests are conducted at the design point and head, power, torque, efficiency and rotational speed are measured. Second circuit is for observation of cavitation phenomena at off-design conditions. Cavitation flow is one of the most important parameters that affect the performance and life span of the turbine components because it causes flow instabilities, vibration, and erosive damage, especially at the runner blades and the draft tube [4]. Therefore cavitation test rig is an important part of all hydroturbine test centers.

II. AIM OF THE STUDY

The Hydro Energy Research Laboratory is responsible for CFD aided design, manufacturing and standardized performance tests of model hydraulic turbines. The hydroturbine design process at the test center is mainly composed of five steps: preliminary design, CFD aided design, model-prototype similarity analysis, model manufacturing and model tests according to International Electrotechnical Commission (IEC) standards.

In this paper, firstly, a brief description of cavitation phenomena in Francis turbines is given. Then, based on the literature survey, cavitation detection and measurement methods are explained. The details of the mechanism used for the cavitation tests of the turbines are presented. Finally, model test procedures and determination of model dimensions according to similitude principles of model and the prototype are briefly described.

III. CAVITATION

Hydraulic cavitation is a result of the state when water pressure drops below the critical pressure (generally vapor pressure) at constant temperature and vapor cavities are formed and grow based on the dynamic pressure reduction. These cavities stop to grow in a liquid flow when pressure rises again and they collapse and disappear. Implosion of the bubbles near solid surfaces causes surface erosion which damages the turbine. Cavitation types in hydraulic turbines can be classified as; travelling bubble, sheet, super, bubble ring, band, fixed patch, travelling patch, spot, cloud, tip vortex, vertical and shear flow cavitation. Travelling bubble, sheet, super, band, fixed patch, and spot types of cavitation are known as blade surface cavitation [12].

A. Cavitation in Francis Turbines

Generally, cavitation is present at the low local pressure zones of the runner blade inlet because of high incidence and at the tip clearance and zones of strong streamline curvature which is the casing between guide vanes and runner [3]. In order to define a mathematical expression for hydraulic turbine cavitation, cavitation number (Thoma number) is derived by using Bernoulli equation and similarity formulae [13].

$$\sigma = \frac{\frac{P_{tw}}{\rho g} - H_s - \frac{P_{wv}}{\rho g}}{H} \quad (1)$$

where P_{tw} is atmospheric pressure, P_{wv} is vapor pressure, H_s is suction head, which is the head difference between turbine runner and tail water, H is the head value, ρ is the water density and g is the gravitational acceleration. Instant cavitation number (σ) is multiplied with a safety factor that is generally taken as 1.1 to 1.2. For high head turbines, it can be increased to 1.5 to 1.7 [13].

Cavitation free results can be seen at the design point of the turbine. However, we cannot say the same thing for off-design conditions. In Figure 1, possible cavitation regions due to the ranges of operation are shown on discharge factor versus speed factor graph. Discharge factor (Q_{ED}) and speed factor (n_{ED}) are defined as:

$$n_{ED} = \frac{nD}{\sqrt{E}}, Q_{ED} = \frac{Q}{D^2\sqrt{E}} \quad (2)$$

where; n is the rotational speed, E is the specific energy, and Q is the flow rate. The main types of cavitation which can occur in Francis type turbines are Leading Edge, Travelling Bubble, Draft Tube Swirl, Inter-blade vortex and trailing edge cavitation [14]. In Figure 2, types and locations of cavitation are given.

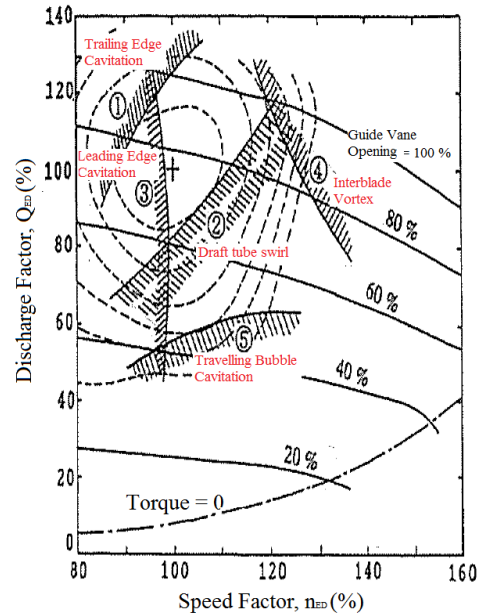


Fig. 1. Francis Turbine off-design range and cavitation types that occur at specified range [Adapted from 14]

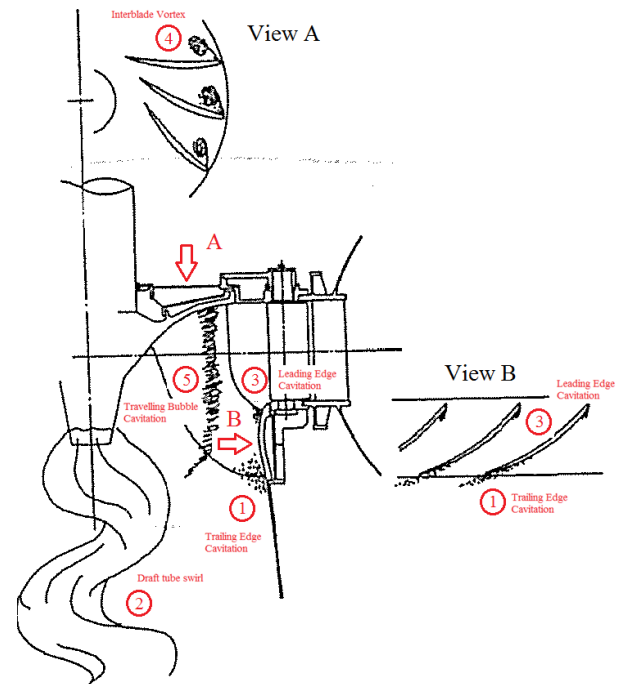


Fig.2. Francis Turbine cavitation types [Adapted from 14]

i) *Leading Edge Cavitation:* When the turbine operation head is greater than the design head, a vital cavitation occurs at the suction side of the runner based on positive incidence

angle (operating range 3). Leading edge cavitation can form at lower operating head values at pressure side of the runner caused by negative incidence angle [14].

ii) *Draft Tube Swirl Cavitation*: This type of cavitation occurs at the outlet of the runner and at the inlet of the draft tube (operating range 2). Its effect depends on the circumferential velocity component of the flow discharged from the runner. This type of cavitation produces pressure pulsation and power fluctuations [14].

iii) *Inter-Blade Vortex Cavitation*: In the operating range 4, due to flow separation, secondary vortices are formed between the blades (see Figure 2). If these vortices touch the blade edges, then this type of cavitation can be harmful. In the high head operating range, vortices become unstable and this is harmful [14, 15].

iv) *Travelling Bubble*: In the operating range 5, (see Figure 1), travelling bubble cavitation occurs in the low head operating conditions. According to small flow angles of attack, flow separation arises in the runner blade. It causes heavy vibration and damage.

v) *Trailing Edge Cavitation*: Operating range 1 represents trailing edge cavitation. In this type of cavitation, if the cavitation occurs only in the trailing edge of the blade, cavities collapse in the draft tube and no serious damage occurs. If the cavitation region reaches the upstream of the blade it can be dangerous. The occurrence range and the location of this type of cavitation are shown in Figures 1 and 2 [14].

IV. TOBB ETU CENTER FOR HYDRO ENERGY RESEARCH

The test rig at the ETU Hydro has a maximum pumping power of 2 MW, test heads up to 160 m and a maximum flow rate of 2m³/s. It can be operated in three different test modes as performance mode, calibration mode and cavitation mode. The modes of operation are detailed below.

A. Performance Test Mode (Open Circuit)

The open circuit test setup consists mainly of high head and low head tanks, model turbine, and pumps (Figure 3). The model turbine which is mounted between high head and low head tank must have geometric similarity with the prototype. The quantities measured during performance tests are discharge, head, torque, efficiency and rotational speed. According to the model test results universal operating characteristics are obtained by plotting hill charts.

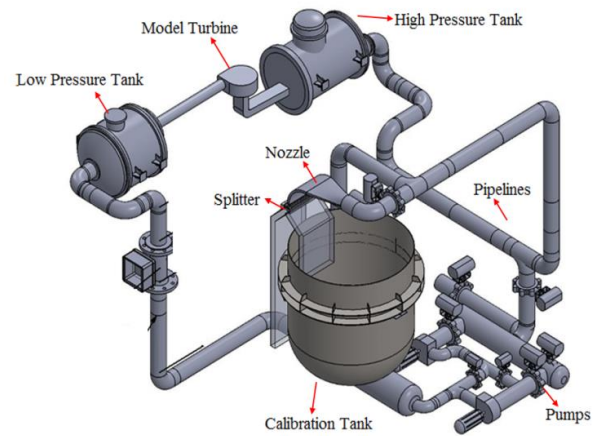


Fig. 3. TOBB ETU Hydro Energy Test Rig

Hydraulic similitude

In the model tests, model turbine should reflect the full scale turbine for meaningful results. For this purpose, a scaled model should have fully similar geometric, kinematic and dynamic attributes to eliminate scaling effects [16]. According to IEC 60193 standards [11], to achieve hydrodynamic similarity between two hydraulic machines these two machines should have geometrical similitude and all of the force ratios should be identical.

In-house codes are developed based on similarity laws to obtain the model turbine parameters. Kinematic condition for the similarity of turbine modes of operation is given as:

$$\frac{Q_2}{Q_1} = \left(\frac{N_2}{N_1} \right) \left(\frac{D_2}{D_1} \right)^{1/3} \quad (3)$$

where; N is rotational speed, D is runner diameter, and Q is flow rate. Subscript 1 denotes prototype properties and subscript 2 denotes model properties.

By modifying the discharge similarity, power and rotational speed ratio similarities are formulated as in equations (4) and (5):

$$\frac{N_2}{N_1} = \left(\frac{D_1}{D_2} \right) \sqrt[3]{\left(\frac{H_2}{H_1} \right)} \quad (4)$$

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1} \right)^3 \left(\frac{D_2}{D_1} \right)^5 \quad (5)$$

where; H is head and P is power. The efficiency terms are neglected due to the difference between efficiencies being smaller than 2%.

The presented similarity laws are used to determine the model turbine parameters of two actual hydroelectric power plants in Turkey (Buski and Gelinkaya). The results are given in Table 2.

TABLE II
PROTOTYPE AND MODEL TURBINE PARAMETERS FOR BUSKI
HEPP AND GELINKAYA HEPP

	BUSKI HEPP		GELINKAYA HEPP	
	prototype	model	prototype	model
D(mm)	580	390	784	325
Q(m³/2)	2	0.89	4.5	0.63
H(m)	78	75	81.8	55
N(rpm)	1000	1458.3	750	1483.5
P(kW)	1400	597	3547	336

B. Calibration Test Mode

Measurement instruments in hydro turbine test rigs need to be calibrated according to International Electrical Commission (IEC) standards [11]. Calibration test mode is mainly for flow meter calibration. In this circuit, after giving its hydraulic energy to the turbine, water goes to the flow diverter mechanism (see Figure 3) and water is diverted to the calibration tank. The mass of the water collected in the calibration tank is measured with the help of load cells which are located below the calibration tank. Also, the filling time of the calibration tank is recorded. Consequently, the flow rate is calculated from the weight of the collected water and the filling time and it is compared with the digital flowmeter readings. Design of the calibration test circuit is detailed in ref [17].

C. Cavitation Test Mode (Close Circuit)

The cavitation test setup is composed of model turbine, high head tank, low head tank and vacuum pump. While conducting experiments with the cavitation test rig, a vacuum is created in the low head tank artificially. To create this vacuum, vacuum pump is mounted to the low head tank and p_{tw} is decreased. While pressure is changed, the head and rotational speed are maintained constant. With decreasing p_{tw} , as it is given in equation 1, σ_{op} is changed. Using σ_{op} values, cavitation coefficient versus efficiency graph is obtained (Figure 4). While mode of operation (σ_{op}) is decreased, efficiency remains constant at a critical σ value. After this critical value, efficiency starts to drop and cavitation occurs.

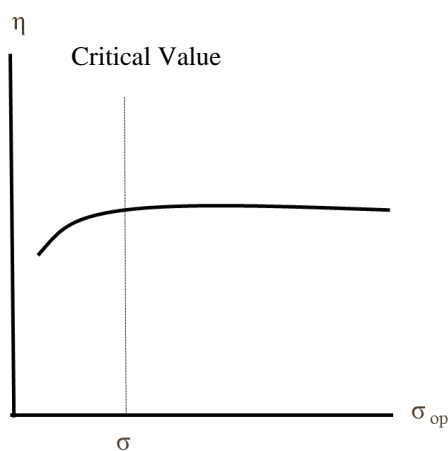


Fig. 4. Efficiency versus cavitation coefficient graph [Adapted from 13]

Cavitation onset and location is not easy to detect due to operating condition, turbine behavior and design of the turbine. Therefore both quantitative and qualitative observations are necessary to detect cavitation zone and the

type of cavitation. As a quantitative technique, velocity and pressure fluctuations at various locations are measured. According to Escaler et al [9, 18], measured signals can be contaminated by noise coming from external sources and therefore choosing an accurate sensor and sensor placement are crucial.

i) Draft tube swirl cavitation detection technique: As a qualitative technique, draft tube inlet (runner outlet) will be transparent and visualization of the cavitation becomes possible. Also a high frame rate camera is placed in the draft tube wall. With this technique, draft tube swirl cavitation can be detected and observed easily. In the draft tube swirl, a large oscillating vortex arises which causes pressure oscillations. Therefore, as a quantitative technique, pressure data are collected in the draft tube wall with pressure transducers.

ii) Leading edge cavitation detection technique: In this technique, accelerometers are mounted on the guide vane and on the turbine guide bearing in both radial and axial directions. With turbine guide bearing measurements, leading edge cavitation, one of the most hazardous cavitation types, detection becomes possible which produces vibrations in the runner.

iii) Travelling bubble cavitation detection technique: Travelling bubble cavitation, which starts from guide vane and extends to the runner blades, can be detected with an accelerometer mounted on the guide vane. Moreover, draft tube pressure pulsations can be the reason of the travelling bubble cavitation which forms between runner blades.

iv) Inter-blade vortex cavitation detection technique: Pressure measurement pads are glued to the runner blades. When separation takes place pressure fluctuations are seen and after separation, negative pressure zones arise. Therefore a pressure measurement is a sufficient method to detect inter-blade vortex cavitation.

v) Trailing edge cavitation detection technique: In this type of cavitation, cavities collapse in the draft tube therefore draft tube swirl detection techniques are also used for this cavitation type. Also hazardous type of the trailing edge cavitation develops upstream of the runner blade. To detect this type of trailing edge cavitation acoustic emission sensor is used. This device measures cavitation sound and audible sound in the form of sound pressure level. According to Escaler et al [9], a frequency band from 10 to 15 kHz is defined as a high frequency content which can be measured by acoustic emission sensors. Also trailing edge and leading edge cavitation types can be in a weak mode which cannot be detected precisely due to their low intensity.

V. CONCLUSION

The TOBB ETU Hydro Energy Research Laboratory is responsible for the computational fluid dynamics aided design, manufacturing and standardized tests of model hydraulic turbines. The hydroturbine design process at the test center is mainly composed of five steps: preliminary

design, CFD aided design, model-prototype similarity, model manufacturing and model tests. In this paper model-prototype similarity laws and test rigs are described. Also cavitation phenomenon, which is formation of bubbles in low pressure regions and collapse in high pressure regions, is described briefly for Francis type turbines. Cavitation detection and measurement methods are given in detail. Accelerometer, acoustic emission sensors, pressure transducers are used to monitor pressure fluctuations, vibrations, and sound pressure levels which are induced by cavitation.

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