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Flow Measurement and Instrumentation

Accuracy analysis of a physical scale model using the example of an asymmetric orifice

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ABSTRACT

For a throttled surge tank of a high-head power plant in Austria the local head loss for an asymmetric orifice has to be quantified and optimized. The physical scale model tests (1:25) of nine different orifices are used as a validation experiment for 3D-numerical simulations (ANSYS-CFX). The increased requirements for the comparison of these two model assumptions lead to an extended accuracy analysis of the hydraulic model test. Based on Bernoulli's equation, theoretical error terms are added to the measured variables (differential pressure and discharge) and thus the measurement accuracy of different instrumentations was tested. The verification of the scale test is based on long-term observation. These tests include the measurement of the vibration of the scale model and an investigation of the temporal offset between the different types of measurement instruments. The results are also examined with the help of a sensitivity analysis.

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1. Introduction

1.1. Overview and application

A surge tank is added to the hydraulic system of a high-head power plant in order to reduce the effects of water hammer from the penstock down to the power house. Thus, the construction cost for the headrace power tunnel can be minimized. The simplest option is to add a chamber with a uniform cross-section which is open to the atmosphere. This hydraulic structure acts like an additional reservoir. If large volumes for water storage are required, the application of a surge tank with chambers is a good solution to compensate heavily varying water levels in the reservoir. Especially for peak-load pumping storage power plants, a throttled surge tank is an economic way to offer a non-restricted operation. To reduce the mass oscillation of the flow, orifices can contribute additional local head loss. Consequently, the required volume of the chambers in the surge tank is reduced to its minimum. To optimize the damping effect, asymmetric behavior of the loss allows an increased loss at reverse flow situations. This layout is typical for high-head power plants in Austria [1].

The TIWAG-Tiroler Wasserkraft AG, a producer of electricity from hydropower, is building up a new penstock and surge tank for an existing power plant (Fig. 1). Part of this project is to add a new asymmetric orifice which is placed at the top of a 90°-elbow in the new surge tank. The radius of the elbow is 7.0 m and the diameter of the nearly horizontal lower chamber is 5.0 m. A shaft (diameter 6.3 m) leads to the upper chamber of the surge tank. The maximum design discharge through the orifice is $Q_{max} = 140$ m³/s.

The aim of the design process is the quantification and optimization of the local loss depending on the flow direction. Three different methods can be used to assess the local head loss coefficient: (a) literature values, (b) scale model tests and (c) numerical simulations.

As a first assumption, tabular values are applied for the local head loss coefficients. The comparison of different literature sources for tabular values and preliminary numerical simulations was presented by Gabl et al. [3]. Instead of starting with a physical scale model, the new approach, namely to begin with a numerical simulation, was integrated into the design process [2]. Thanks to the use of 3D-numerical software, a wide range of geometry variation could be implemented and thus the optimization reached good results. Therefore, the commercial code ANSYS-CFX was used. This frequently used software solution facilitates for example the simulation of fluid–structure interaction and optimization of blades [4,5]. ANSYS-CFX is also validated for various cases including free surface flow [6–8].

Based on the preliminary numerical simulations, hypotheses for the design of asymmetric orifices are formulated [9]. In order

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Nomenclature

		r	radius (m) or ratio (-)
		t	time (s)
A	area (m^2)	v	velocity (m/s)
B	width (m)	z	elevation (m)
f_h	error in measurement of height (m)	α	energy correction factor (-)
f_p	error in measurement of differential pressure (N/m^2)	β	constant (m^{-4})
	or (mbar)	χ	local head loss coefficient (s^2/m^5)
f_Q	error in measurement of discharge (l/s) or (m^3/s)	ζ	local head loss coefficient (-)
g	gravitational acceleration ≈ 9.81 (m/s^2)	Δt	time step (s)
h	head (m)	θ	angle (°)
p	pressure (N/m^2) or (mbar)	λ	ratio of loss coefficients (-)
Δp	differential pressure (N/m^2) or (mbar)	ν	discharge coefficient (-)
P	height of sill (m)	ρ	mass density of water ≈ 997 (kg/m^3)
Q	discharge (l/s) or (m^3/s)		

to verify them, nine different orifices are chosen. This is followed by a detailed numerical simulation as well as a physical scale test. These results are then compared with those from the numerical simulation. The main goal of the investigation is to validate the two model assumptions (numerical simulation and physical scale model) and as a result to strengthen the confidence in the 3D-numerical methods [9].

1.2. Key aspects

The main focus of the presented work is on the comparability and accuracy of the measurements of the local head loss coefficient of an asymmetric orifice in the laboratory. In this regard the starting point of the preparation is to check if the used instruments (discharge Q and differential pressure Δp) are as accurate as needed. Therefore, equations are set up with a theoretical error approach. After building up the scale test in the laboratory, these assumptions have to be verified with the help of a long period measurement and afterwards checked with a sensitivity analysis.

1.3. Scale of the hydraulic model

In general, to scale the model for pipe flow, the Reynolds similarity has to be used [10]. Therewith, the maximum discharge $Q_{max,Nature} = 140$ m^3/s in nature would require a discharge of $Q_{max,Model} = 140/25 = 5.6$ m^3/s in the laboratory. In the presented

case, the investigated local head loss coefficient of the asymmetric orifice is independent of the Reynolds number. Thus, the requirements for the discharge through the model can be reduced [11,12]. Based on this, the experiments were conducted with a variation of discharge between 20 and 70 l/s. The maximum pressure in the model is limited to 7 bar. Fig. 2 shows the cross section of the model and Fig. 3 the actual model. To use this model as a validation experiment, the numerical model simulates the hydraulic model at scale 1:1. Thus, scale effects have no influence on the comparison of the numerical and the physical scale model.

2. Theoretical background

2.1. Basic equations

As a starting point Bernoulli's equation (2) for real incompressible fluid is used. This theorem states that the total energy h_E is constant along a steady continuous streamline [13]. The indexes 1 and 2 mark the different points along the streamline (numbered in flow direction). Hence, the losses h_v have to be added in Section 2. The investigated model is turned into the datum plane. Therewith, z_1 is equal to z_2 and the difference will be zero. As a first assumption, the energy correction factors α_1 and α_2 are simplified to 1.0 [-].

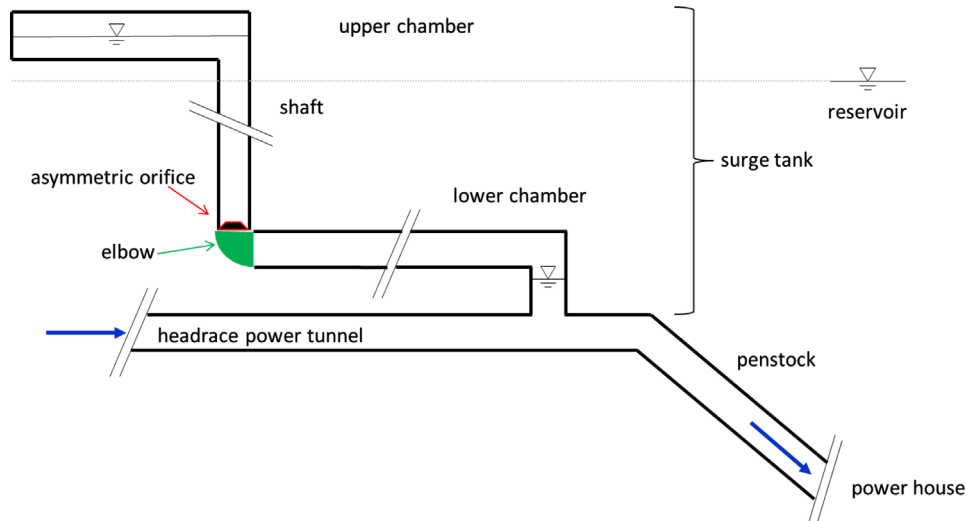$$z_1 + \frac{p_1}{\rho \cdot g} + \frac{\alpha_1 \cdot v_1^2}{2 \cdot g} = h_{E1} = constant = \ldots \tag{1}$$

Fig. 1. Simplified scheme of the surge tank.