6th IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, September 9-11, 2015, Ljubljana, Slovenia

A DYNAMIC BEHAVIOR OF LOW HEAD HYDRO POWER PLANT DURING THE TRANSIENT OPERATIONAL REGIMES

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ABSTRACT

The calculated and measured values of the main working parameters of low head HPP during the transient operational regimes is analyzed in this presentation. The influence of the draft tube in the modeling of the system and corresponding draft tube pressure fluctuation are described.

Using the software simulation several operational regimes are analyzed during the shut down and load rejection of single low head Francis unit. For turbine characteristic modelling the actual turbine model test diagram is used. The calculated results include the values of main turbine parameters, pressure fluctuation in the penstock and the draft tube during the transient regimes.

The measurements of all parameters during the transient regimes are performed at site. An analysis of measured and calculated parameters is performed. The comparison of the calculated values with and without drat tube modelling shows the corresponding differences in the results, against the measured values. A special attention is dedicated to the pressure fluctuation in the turbine draft tube. Possibilities for cavitation and water column separation are indicated during the transient regimes. The experimental results confirm the calculated values.

KEYWORDS

Transient regimes, Francis turbine, runaway, water hummer, modelling

1. INTRODUCTION

Hydropower plants have relatively steady power output in the electric power system and therefore, units (turbine-generator) are more often working at maximum power, load changes and a large number of starts and shut-down of the units. The accurate definition of the dynamic behaviour of the power plant and its units, taking into account various aspects of operation is an essential requirement for the design, performances and control of hydropower plants (HPPs). During switching from one operation regime of the HPP to another, unsteady processes in intake and tail water structures are initiated changing the dynamics of the unit.

The calculated and measured values of the main working parameters of low head HPP during the transient operational regimes is analyzed in this presentation. The influence of the draft tube in the modelling of the system and corresponding draft tube pressure fluctuation are described.

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2. MODELLING OF THE HPP HYDRAULIC COMPONENTS

The mathematical (numerical) model of basic hydraulic components of the power plant is presented here in more detail.

2.1 Pipe model

Mathematical model for unsteady flow in pipe is obtained using a one-dimensional approach of modelling with conservation laws for mass flow (continuity equation (eq.1)) and momentum (motion equation (eq.2)). These two equations set for elementary particle in hydraulic pipes are as follows [1]:

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0 \tag{1}$$

$$\frac{\partial H}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{\lambda Q|Q|}{2gDA^2}=0 \tag{2}$$

The hyperbolic set of equations (1) and (2) are quasi-linear hyperbolic functions and can’t be solved with a general analytical solution, but given initial and boundary conditions, can be calculated numerically, often using a finite differences method (characteristics method) [2].

2.2 Valve model

The discharge of a valve at steady state conditions is [3]:

$$Q_0=\left(c_Q\right)_0\cdot \mathrm{A}\cdot\sqrt{2gH_0} \tag{3}$$

where c_Q is valve discharge coefficient.

The valve discharge coefficient depending on valve characteristics i.e. valve opening/closing law τ(t) [3]:

$$c_Q(t)=\tau(t)\cdot\left(c_Q\right)_0 \tag{4}$$

The discharge of a valve at unsteady state conditions is given with following equation [3]:

$$Q_v=c_{Q(t)}\mathrm{A}_{(t)}\sqrt{2gH} \tag{5}$$

2.3 Francis turbine model

Transient regimes in the electric power system initiate unbalanced torque between turbine and generator, thereby increasing the rotating speed, changes according to the angular momentum equation for the rotating mass according to the following equation [4]:

$$\mathrm{M}_H-\mathrm{M}_S=J\cdot\frac{d\omega}{dt} \tag{6}$$

After a full load rejection conditions the electromagnetic resistance torque Ms, can be set equal to zero. According to equation (8), the mechanical inertia of unit J (turbine-generator) has a significant influence on the speed variation of the rotating mass of the unit.

The influence of the turbine’s water passage (Fig.1) on the hydraulic system can be defined by one-dimensional approach for modelling through the continuity and motion equation. The head (pressure) pulsations in hydraulic installation from the turbine are represented as [5]:

$$\Delta H = 2\left[\frac{1}{k_Q^2 D^4 g}\right] Q_2|Q_1| - \left[\frac{1}{k_Q^2 D^4 g}\right] Q_1|Q_1| \tag{7}$$

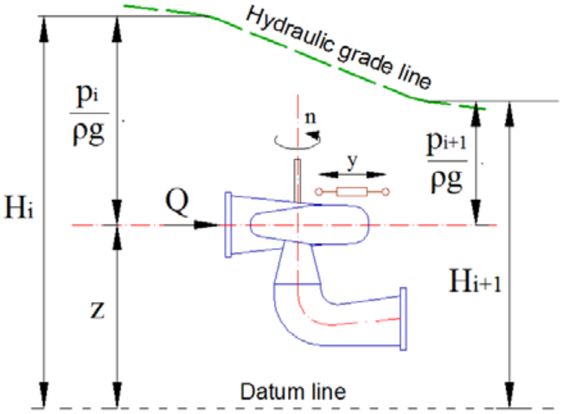

Fig.1 Francis turbine model

where: ΔH is the head fluctuations between two point of computation, k_Q is discharge turbine coefficient computed from turbine characteristics (Fig. 2) and expressed as function of guide vane opening and discharge value, Q_1 and Q_2 are the discharge values in the previous step from the computation and current discharge, D is the turbine runner diameter.

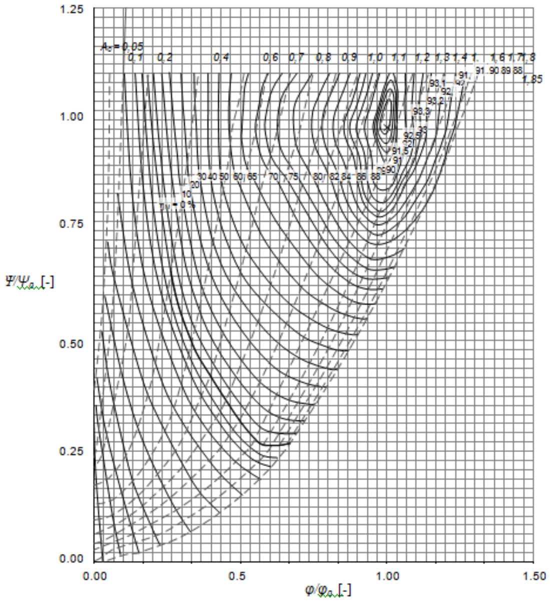

Fig.2 Francis turbine hill chart of HPP Sv. Petka

The characteristic (hill chart) of the turbine (Fig. 2) can be defined as function of guide vane opening position A_0 and the discharge coefficient φ and head coefficient Ψ [4]:

$$\varphi = \frac{Q}{\frac{\pi^2}{4} n^2 D^3} \quad and \quad \Psi = \frac{gH}{\frac{\pi^2}{4} n^2 D^2}; \tag{8}$$

2.4 Turbine draft tube modelling

One of the major difficulties in the turbine modelling is the existence of a vortex rope (gaseous volume) in the draft tube at off-design operating conditions. The vortex rope produces undesirable, periodic pressure pulsations (pressure surges) within the draft tube.

These pressure pulsations produce existing forces that can affect components of the all systems of a hydroelectric power plant.

Using one-dimensional approach the turbine draft tube modelling can be defined as pressure source excitation in series with two pipes that requires the length and cross section obtained from the draft tube geometry and the wave speed, as input parameters. Modelling of the vortex rope gaseous volume is based on the assumption that the gaseous volume V depends of the state variables H (the net head) and Q (the discharge). The rate of change of the gaseous volume is given by the variation of discharge between the 2 fluid sections limiting the rope (Fig.3), [5,6,7]:

$$\frac{dV}{dt} = Q_1 - Q_2 = C\frac{dH_2}{dt} + \chi\frac{dQ_2}{dt}; \tag{9}$$

where: $C = -\partial V/\partial H$ is cavity compliance and $\chi = -\partial V/\partial Q_2$ is mass flow gain factor. Inertia and friction loss effects of the gas volume are negligible, i.e. $H_2 = H_1$.

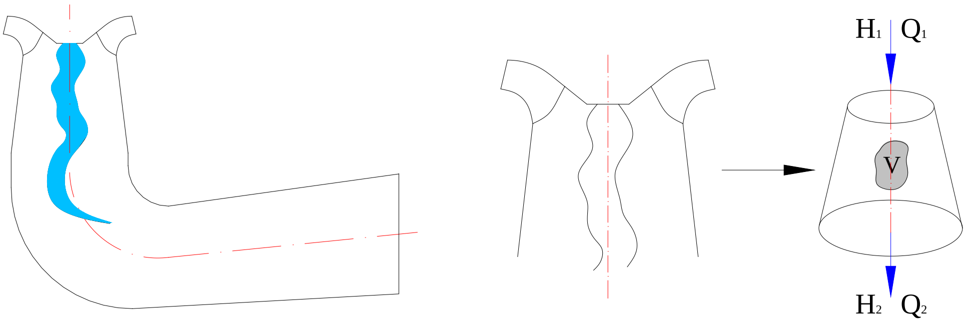

Fig.3 Turbine draft tube model and vortex rope gaseous volume [7]

3. NUMERICAL SIMULATION OF THE TRANSIENT OPERATIONAL REGIMES

The case study of the HPP operation presented here investigates units with vertical Francis turbines and rated capacity of 18.9 MW and flow rate of 50 m^3/s. A complete model of the hydropower plant with all corresponding elements is shown in Fig.4. The HPP consists of the following hydraulic components: upstream reservoir (accumulation), penstock (pipeline), Francis turbine and downstream reservoir (tailrace). Technical characteristics of the hydropower plant are given in Tab.1.

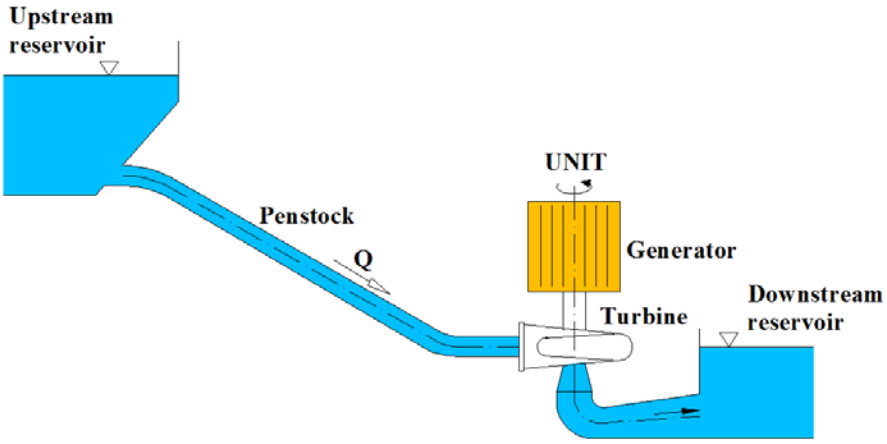

Fig.4 Layout of the hydropower plant

Tab.1 Characteristics of HPP (rated values)

Upstream reservoir	**Penstock**	**Turbine**	**Generator**
H_{max}=43 [m]	L =30 [m] D= 3.3 [m]	H_0=40 [m] n_0=214 [min^{-1}] Q_0=50 [m^3/s] P_0=18.9 [MW]	J_G=710 [tm^2] J_T = 30 [tm^2]

Numerical simulation of the transient regimes is performed using the WHAMO (model 1) and SIMSENHydro (model 2) software packages [5] [9]. The time step (Δt=0.005 [s]) is determined from the Lewy-Courant criteria [1], that is Cr<1:

$$\boldsymbol{\Delta t < \frac{L}{a \cdot n}; \qquad C_r = \frac{a \cdot \Delta t}{\Delta x} < 1} \tag{10}$$

where n represents the number of segments that penstock is divided in, while Δx is the length of one segment.

Numerical model of HPP defined in the software packages presented in Fig.5 and Fig.6.

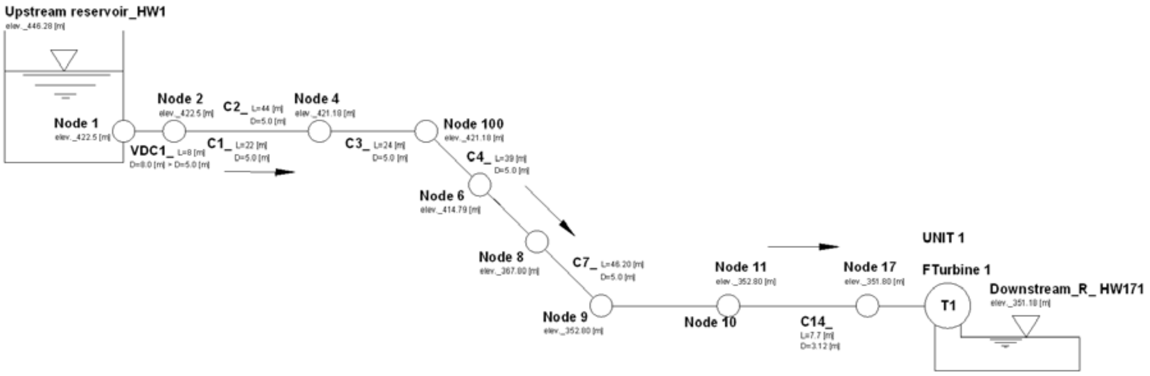

Fig. 5 Numerical model of HPP (Whamo model)

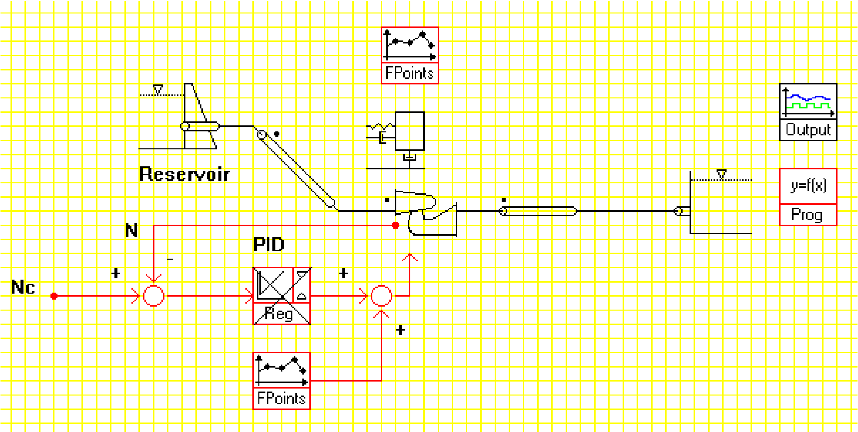

Fig.6 Numerical model of HPP (SIMSENHydro model)

The transient phenomena of the power plant were simulated for scenario with load rejection of the unit from maximum power. The guide vanes closing law (y) after load rejection is shown in Fig.7. The results of the numerical simulation and experimental data [8] for pressure change at the inlet of turbine are presented in Fig.8.

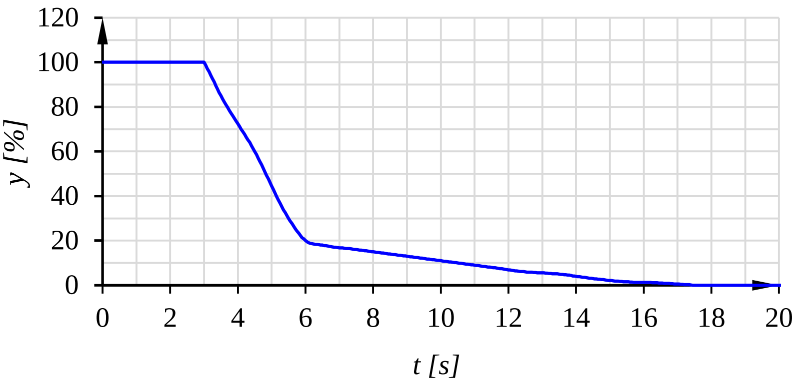

Fig.7 Guide vanes closing law

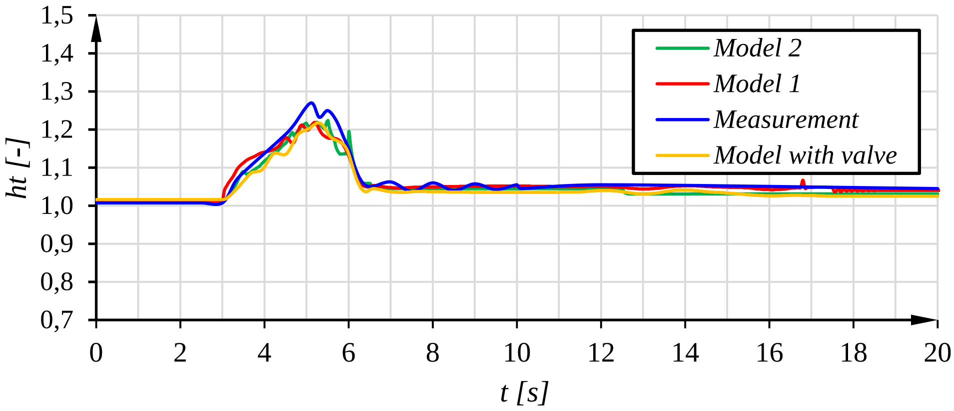

Fig.8 Results for head at the inlet of turbine

In order to investigate the influence with and without turbine modelling a valve simulation with the same closing characteristic was performed. The difference in the results can be seen very clear in Fig. 8 and Fig. 10.

The results of the numerical simulation and experimental data for rotational speed (runaway) of turbine are presented in Fig.9. The large differences of calculated and measured data after 15 sec closing time are due to the friction losses.

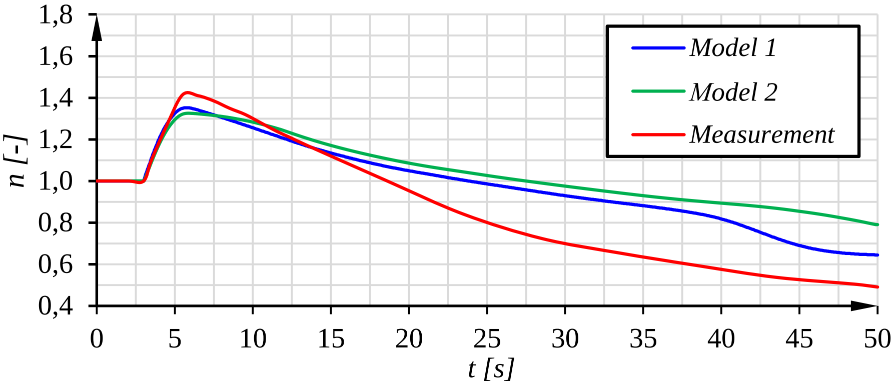

Fig.9 Results for rotational speed of turbine

The results of the numerical simulation and experimental data for pressure change in the turbine draft tube are presented in Fig.10 and Fig.11. The negative pressure at the inlet of the draft tube is higher in partial load of the turbine (case study 2 in Fig 10).

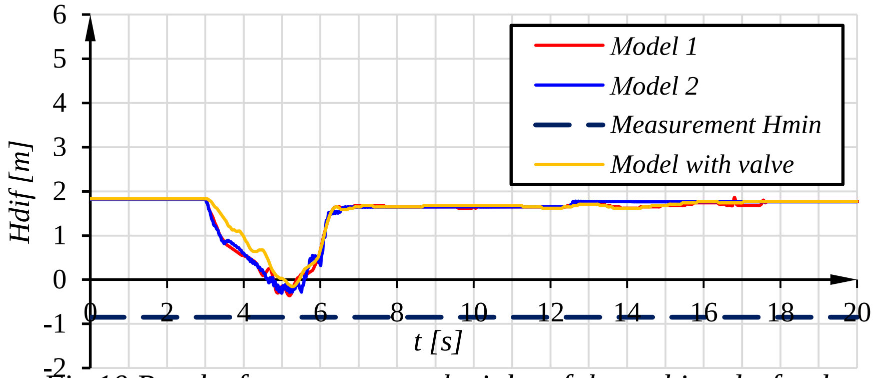

Fig.10 Results for pressure at the inlet of the turbine draft tube

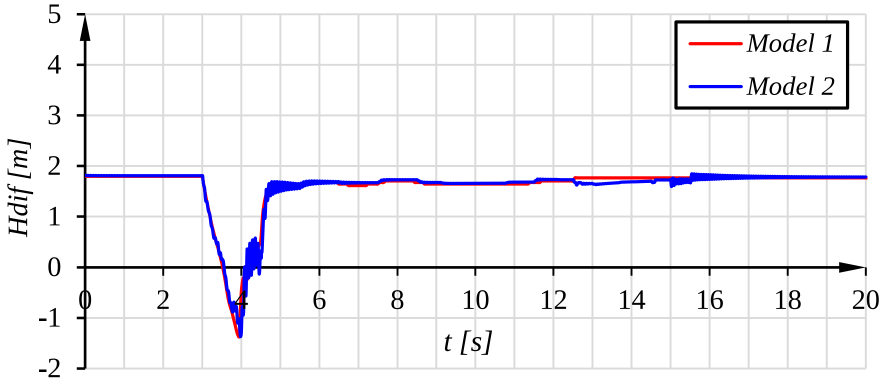

Fig.11. Results for pressure at the inlet of the turbine draft tube (case 2)

The differences between the measured and calculated data of the characteristic values during the transient regimes are presented in table below. The differences of 3,1 to 4,6 percent can be assume as acceptable for engineering practice. Also, the shape of the measured and calculated diagrams match very good each to other. This means that the turbine modelling is very accurate using turbine geometry and model hill chart. In opposite, larger differences occur in case when turbine closing is simulated with valve, even the same closing diagram as actual turbine closing (change of discharge) shown in Fig. 12 is used.

	Measurement	**Model 1 (whamo)**		**Model 2 (simsen)**	
		simulation	difference [%]	simulation	difference [%]
H_{max} [m]	51.0	49.0	**-3.9**	49.4	**-3.1**
H_{min} [m]	43.0	41.5	**-3.5**	41.0	**-4.6**
$H_{d\,min}$ [m]	2.03	-0.3	/	-0.32	/

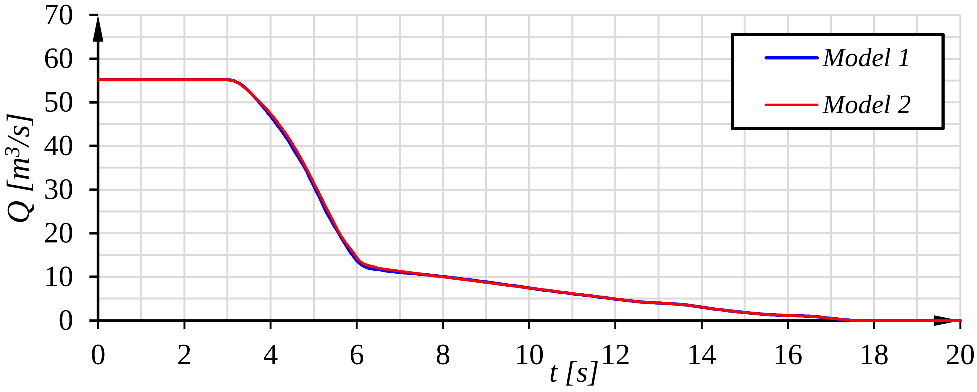

Fig.12 Results for turbine discharge

4. CONCLUSIONS

Based on the investigation presented in this paper several conclusions can be obtained:

1. The numerical simulation models and software packages are useful and reliable tools for calculation of transient regimes in HPP facilities.
2. Accurate modelling of HPP hydraulic components including turbine geometry is very important for accurate simulation results.
3. Turbine characteristic (hill chart) is essential for good modelling of the transient regimes process.
4. Draft tube modelling and simulation results can be very useful as a boundary conditions for CFD calculations of 3D unsteady flow calculation.

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