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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF A WATER HAMMER IN SAVA RIVER KAPLAN TURBINE HYDROPOWER PLANTS

TEORETIČNE IN EKSPERIMENTALNE RAZISKAVE VODNEGA UDARA V HIDROELEKTRNAH S KAPLANOVIMI TURBINAMI NA REKI SAVI

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Keywords: hydropower plant, Kaplan turbine, Sava River, water hammer, validation

Abstract

This paper deals with critical flow regimes that may induce an unacceptable water hammer in the Sava River Kaplan turbine hydropower plants. The rigid water hammer model is introduced first. The computational results are then compared with the results of measurements in two distinct hydropower plants (HPP): (i) The refurbished and upgraded Medvode HPP, and (ii) The newest Brežice HPP. Comparisons of the computed and measured results are examined for normal operating regimes. The water hammer in the two power plants is controlled by appropriate adjustment of the wicket gates and runner blades closing/opening manoeuvres. The agreement between the computed and measured results is reasonable.

Povzetek

Prispevek obravnava kritične pretočne režime, ki lahko povzročijo nesprejemljiv vodni udar v hidroelektrarnah s Kaplanovo turbino na reki Savi. Najprej je predstavljen model togega vodnega udara. Računske rezultate nato primerjamo z rezultati meritev v dveh značilnih hidroelektrarnah

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(HE): (i) prenovljeni in nadgrajeni HE Medvode ter (ii) najnovejši HE Brežice. Primerjave izračunanih in izmerjenih rezultatov so podane za normalne režime obratovanja. Vodni udar v obeh elektrarnah je krmiljen z ustrezno nastavitvijo manevrov zapiranja oziroma odpiranja vodilnih in gonilnih lopatic turbine. Ujemanje med izračunanimi in izmerjenimi rezultati je dobro.

1 INTRODUCTION

Hydropower is a key renewable energy asset in Slovenia capable of meeting long term, and, in particular, intermittent electrical power demands. In the European Union it accounts for about 12 % of electricity production. In addition, it offers flexibility and storage of energy, which are important for maintaining the stability of the electrical grid system, due to the growing share of variable renewable energy sources [1]. In the light of safe and flexible operation of hydropower systems this paper deals with water hammer events in the Kaplan turbine hydropower plants installed on the Sava River in Slovenia. The Sava River basin is the largest in Slovenia and represents more than 50% of the total country area, but is the least utilised in terms of hydropower, with a total installed capacity of 230 MW [2]. The Sava River hydropower plants with Kaplan turbines are (from north to south): Mavčiče HPP (1968, 2x19 MW), Medvode HPP (1953, upgraded and refurbished 2004, 2×12.4 MW), Arto-Blanca HPP (2008, 3x13 MW), Krško HPP (2012, 3×13 MW) and Brežice HPP (2017, 3×15.2 MW). Completion of the chain on the lower Sava River is underway, and the start of the procedure for the design of the middle Sava River chain with 10 hydropower plants is foreseen in the near future.

Water hammer control is essential, to assure safe and flexible operation of the new, as well as the refurbished and upgraded hydropower plants. Large transient loads may disturb the overall operation of the plant (operational range) and damage the system components, for example, distributor vanes or runners. Hydraulic transients in hydropower plants with Kaplan turbines can be kept within the prescribed limits (pressure in the flow passage-system, turbine rotational speed, etc.) with the following methods [3], [4], [5]:

- *Alteration of operational regimes*. This method includes typically appropriate control of the wicket gate and runner blade manoeuvres (the turbine governor and servomotor mechanism). A two- or multi-speed wicket gate closing time function (adding a cushioning stroke) improves the safe operation of the plant significantly. Opening of the runner blades during the turbine shutdown (normal, mechanical quick stop, emergency) results in a favourable runner blade manoeuvring, improved over-speed performance and reduced negative axial hydraulic thrust.
- *Installation of surge control devices in the system*. A draft tube gate can be used to protect a Kaplan turbine against runaway. In addition, sluicing operation of the low-head Kaplan turbines can attenuate open channel waves during transient regimes. Surge control devices alter the system characteristics (shorten the active conduit length, reduce the liquid compressibility, increase the turbine inertia, etc.). The protective devices that may be installed along the inlet and outlet conduit or added to the system components are increased turbine unit inertia, a surge tank (in HPPs with long conduits), a pressure regulating valve, aeration pipe, air valve, etc.
- *Redesign of the flow passage system layout* includes a change of the conduit profile (high point) and dimensions (diameter, length), and different positioning of the system components (for example, valves).

A traditional water hammer control device, particularly in the case of refurbishment and upgrading of Kaplan turbines, is the turbine governor coupled to the wicket gate and runner blade servomotor mechanisms [6], [7], [8], [9]. The control devices should operate smoothly in the following normal operating conditions [4]: turbine start-up, load acceptance, load reduction and total load rejection (mechanical quick stop, electrical emergency shutdown). Emergency conditions are load rejections in which partial runaway occurs. The turbine runaway is considered as a catastrophic transient regime. Water hammer analysis should be performed for normal, emergency and catastrophic operating conditions.

The main objective of this paper is to identify critical flow regimes that may induce unacceptable water hammer in the Sava River Kaplan turbine hydropower plants. The rigid water hammer model [3], [10] is introduced first. The computational results are then compared with the results of measurements in two distinct HPPs: (i) The refurbished and upgraded Medvode HPP, and (ii) The newest Brežice HPP. Comparisons of the computed and measured results are examined for normal operating regimes.

2 THEORETICAL MODELLING

The water hammer in hydropower plants equipped with axial turbines (Kaplan, bulb) can be calculated using either the elastic [11] or rigid [10] water hammer theory. The run-of-river power plants are, traditionally, comprised of relatively short inlet and outlet conduits. The length of the conduit is of the same order as the cross-sectional dimensions, as is the case for the Medvode HPP and for Brežice HPP. The cross-sectional area is of a complex shape. The standard one-dimensional elastic water hammer model cannot predict the physics of wave transmissions and reflections accurately [12]. The rigid water hammer model is recommended to be used for this case [10]. Incompressible liquid and rigid pipe walls are assumed in the model. Rigid water hammer is described by the one-dimensional equation of motion for unsteady pipe flow [3]:

$$\frac{\partial H}{\partial x} + \frac{fQ|Q|}{2gDA^2} + \frac{1}{gA}\frac{dQ}{dt} = 0 \tag{2.1}$$

in which H = pressure head, x = distance, f = Darcy-Weisbach friction factor, Q = discharge, g = gravitational acceleration, D = diameter, A = cross-sectional area, and t = time. Equation (2.1) is solved simultaneously with the dynamic equation of the turbine unit rotating masses, taking into account the discharge and torque turbine characteristics [10]:

$$T_x = I\frac{d\omega}{dt} \tag{2.2}$$

in which T_x = the net torque applied to the turbine unit shaft, I = the polar moment of inertia, and ω = the angular velocity. Steady-state turbine characteristics are used for a transient analysis [13]. There are some discrepancies between the steady and unsteady performance characteristics, due to unsteady flow effects and when the turbine operates in a cavitating region [10]. Transient regimes in the HPP are *relatively slow* (the wicket gates closure time is much slover than the wave reflection time); therefore, the unsteadiness should not affect the turbine's characteristics significantly. The complex axial turbine performance characteristics in zones of normal turbine operation and energy dissipation, and complex flow behaviour of the turbine, particularly at off-design operating conditions, led researchers to develop a full-three-dimensional model for water hammer analysis in axial turbines with relatively short inlet and outlet conduits [14], [15], [16]. The three-dimensional model enables the prediction of flow quantities at an arbitrary computational domain location. The first step was to develop a model for a bulb turbine, because of its *relatively simple* geometry in comparison to the Kaplan turbine geometry (scroll-case, draft tube with elbow). The development of a three-dimensional water hammer model for Kaplan turbines is the subject of the authors' further research in the field of Fluid Transients in Systems.

The geometric characteristics of the inlet (Gu) and outlet (Gd) conduits are decribed by the following equations:

$$G_u = \sum_i \frac{L_{ui}}{A_{ui}} \tag{2.3}$$

$$G_d = \sum_i \frac{L_{di}}{A_{di}} \tag{2.4}$$

in which L = the length of the conduit.

3 COMPARISONS OF THE COMPUTED AND MEASURED WATER HAMMER EVENTS IN MEDVODE HPP

Medvode HPP is located on the Sava River in the town Medvode, 15 km north of Ljubljana. There are two double-regulated Kaplan turbines, each with its own flow-passage system. The plant was built in 1953 with the rated output of each turbine of P_r = 9.3 MW. The diameter of the six-bladed runner was D = 3060 mm. A major refurbishment and upgrading of the two old turbines were performed in 2004. The old turbine runners have been replaced by new five-bladed runners of increased rated output, P_r = 12.43 MW, and increased runner diameter, D = 3250 mm [17]. During the development and design of the new runner special attention was given to reliable, sustainable and environmentally friendly constructional solutions, in order to minimise the unwanted impacts of lubricants on the river water's pollution.

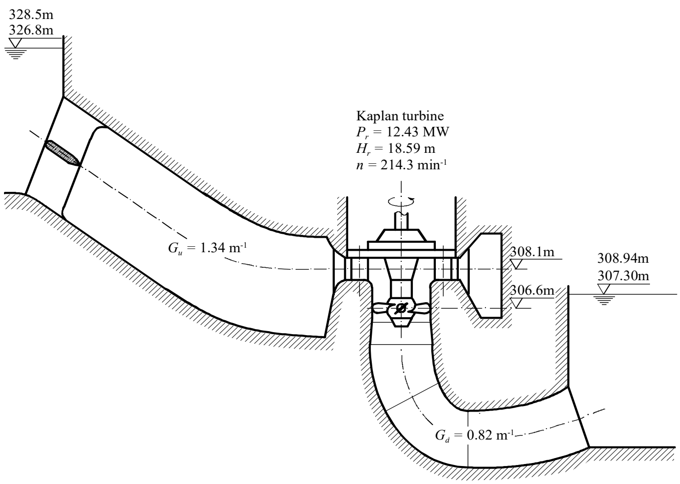

Figure 1: *Medvode HPP flow-passage system of the Kaplan turbine unit*

The flow-passage system of the Medvode HPP is comprised of an upper basin (Lake Zbilje), two parallel inlet conduits, each with a Kaplan turbine unit and draft tube (Figure 1), and tailrace (Sava River). Dynamic loads during the transient regimes are controlled by appropriate adjustment of the wicket gate and runner blade closing/opening manoeuvres. The dimensions of the inlet conduit and scroll-case, and the draft tube, are expressed as the geometrical characteristics G_u = 1.34 m^{-1} and G_d = 0.82 m^{-1} (Equations (2.3) and (2.4)), respectively. The polar moment of inertia of the unit's rotating parts (turbine, shaft, generator) is I = 163×10^3 kgm^2.

A hydraulic transient analysis in the final design stage of the refurbished and upgraded turbine unit was performed for normal, emergency and catastrophic operating regimes [4]. The rigid water hammer model was used for all the computational runs. A number of experimental runs for various transient regimes were carried out in the plant, in order to verify the suitability of the wicket gate and the runner blade closing/opening procedures. The extreme values of the measured quantities during the transients were within the prescribed limits. This paper presents two emergency shutdown case studies [17]. The computational results are compared with the results of the measurements.

3.1 Emergency shutdown of the turbine unit from 13 MW

An emergency shutdown of the turbine unit from the maximum load of 13 MW is the most severe normal operating transient regime with respect to the extreme pressure heads and turbine rotational speed, and, consequently, the danger of full water column separation under the turbine head cover. The turbine is disconnected from the electrical grid, followed by a complete closure of the wicket gates (servomotor stroke (y_{wg})) (Figure 2a). The runner blades (servomotor stroke (y_{rb})) stay still at their fully open position (Figure 2b).

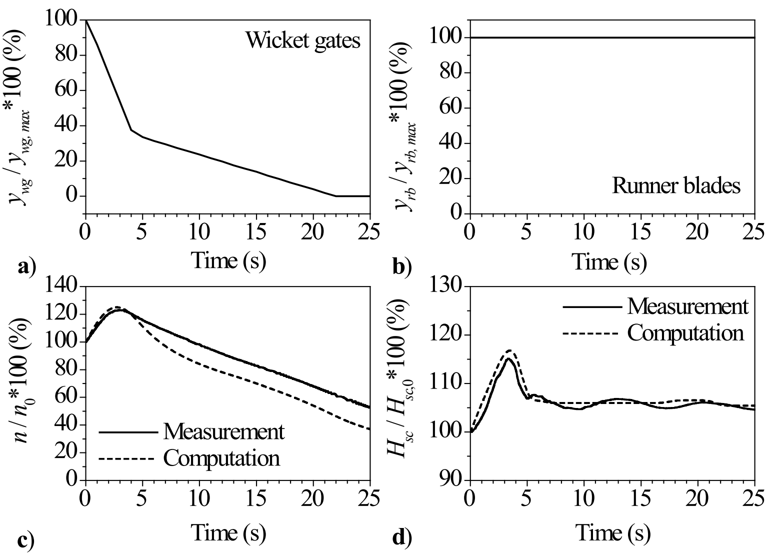

Figure 2: *Emergency shutdown of the Kaplan turbine unit in the Medvode HPP from 13 MW – wicket gate servomotor stroke a), runner blade servomotor stroke b), rotational speed c) and scroll-case pressure head d)*

The turbine rotational speed (*n*) (Figure 2c) and the pressure head in the scroll-case of the turbine (H_{sc}) (Figure 2d) were compared. There was a reasonable agreement between the computed and the measured maximum rotational speed rise of 25.9 % and 23.2 %, respectively (Figure 2c). The computed maximum scroll-case pressure head rise of 17.4 % was higher than the measured pressure head rise of 14.2 % (Figure 2d). The maximum speed rise and the maximum scroll-case pressure head rise were well below the prescribed limits (45 % of the nominal speed and 35% of the maximum gross head, respectively).

3.2 Emergency shutdown of the turbine unit from 6.8 MW

Emergency shutdown of the turbine unit from the half-load of 6.8 MW was investigated, in order to verify the model for a broader range of input parameters. The turbine was disconnected from the electrical grid, followed by a complete closure of the wicket gates (y_{wg}) (Figure 3a). The runner blades (y_{rb}) opened to their fully open position (Figure 3b).

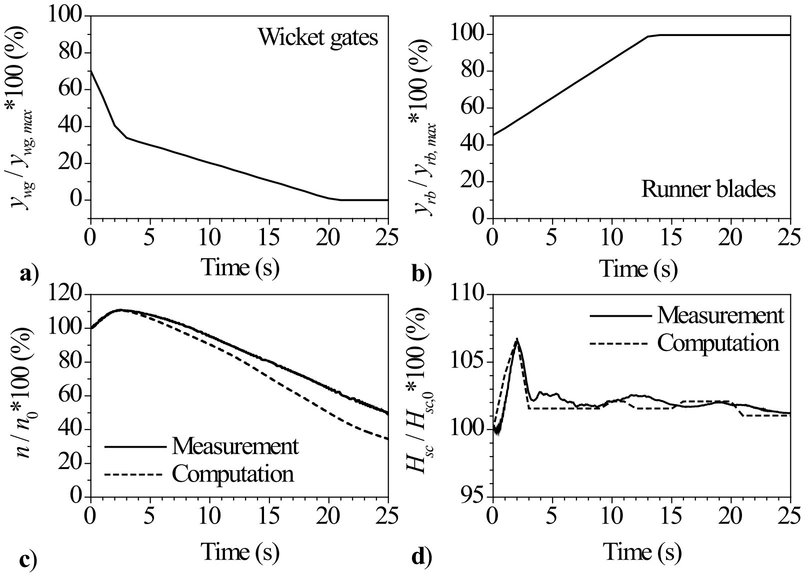

***Figure 3**: Emergency shutdown of the Kaplan turbine unit in the Medvode HPP from 6.8 MW – wicket gate servomotor stroke a), runner blade servomotor stroke b), rotational speed c) and scroll-case pressure head d)*

The turbine rotational speed (*n*) (Figure 3c) and the pressure head in the scroll-case of the turbine (H_{sc}) (Figure 3d) were compared. There was an excellent agreement between the computed and the measured maximum rotational speed rise of 10.9 % and 11.0 %, respectively (Figure 3c). The computed maximum scroll-case pressure head rise of 6.8 % was slightly higher than the measured pressure head rise of 6.5 % (Figure 3d). The maximum speed rise and the maximum scroll-case pressure head rise were well below the prescribed limits (45 % of the nominal speed and 35% of the maximum gross head, respectively).

4 COMPARISONS OF THE COMPUTED AND MEASURED WATER HAMMER EVENTS IN BREŽICE HPP

Brežice HPP is the fifth in a chain of six planned run-of-the river hydropower plants the Slovenian lower Sava River basin. When completed, the 6 hydropower plants will account for 20 % of hydropower energy production in Slovenia. The three Kaplan units, with a total installed discharge of 500 m^3/s and rated power of 15.2 MW each with yearly production of 161 GWh, are controlled by a remote centre in the nuclear power plant Krško. The runner diameter of the four-bladed double-regulated Kaplan turbine is D = 4900 mm. The three turbines have been opearting successfully since 2017. Major additional landscaping and municipal engineering work was performed, in order to provide flood protection, compensate for lost habitat, and make way for possible future tourist development. A fishway, that allows fish and other aquatic organisms to pass the hydropower structure, has been built on the left-hand-side river-bank (relative to the flow direction) – see Figure 4.

Figure 4: *Brežice HPP layout with clearly visible fishway located on the left-hand-side river-bank (relative to the river flow direction) (www.he-ss.si)*

The flow-passage system of Brežice HPP is comprised of an upper basin (Sava River forebay), three parallel inlet conduits, each with a Kaplan turbine unit and draft tube (Figure 5), and tailrace (Sava River). The dynamic loads during transient regimes are controlled by appropriate adjustment of the wicket gate and runner blade closing/opening manoeuvres. The dimensions of the inlet conduit and scroll-case, and the draft tube, are expressed as the geometrical characteristics G_u = 0.52 m^{-1} and G_d = 0.69 m^{-1} (Equations (2.3) and (2.4)), respectively. The polar moment of inertia of the unit's rotating parts (turbine, shaft, generator) is I = 735×10^3 kgm^2.

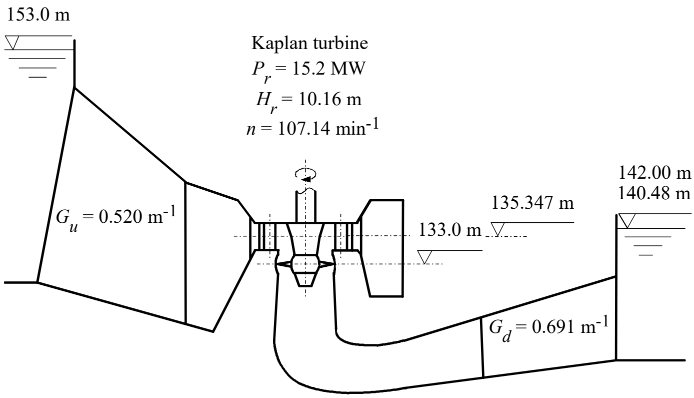

***Figure 5**: Brežice HPP flow-passage system of the Kaplan turbine unit*

Similar to Medvode HPP, the emergency shutdown of the Kaplan turbine unit from the maximum load of 21 MW is considered to be the most severe normal operating regime in Brežice HPP [18]. The maximum load is much larger than the rated one, because the turbine has been optimised for the complete lower Sava River chain, with a much higher tailrace water level. The turbine was disconnected from the electrical grid, followed by the complete closure of the wicket gates (Figure 6a), while the runner blades are opened to their fully open position (Figure 6b). The agreement between the computed and measured maximum unit rotational speed rise of 36.3 % and 35.3 % (Figure 6c), respectively, was very good. The same can be said for the maximum scroll-case pressure head rise; the computed value was 7 % and the measured one was 6.1 % (Figure 6d). The maximum speed rise and the maximum scroll-case pressure head rise were well below the prescribed limits (50 % of the nominal speed and 35% of the maximum gross head, respectively).

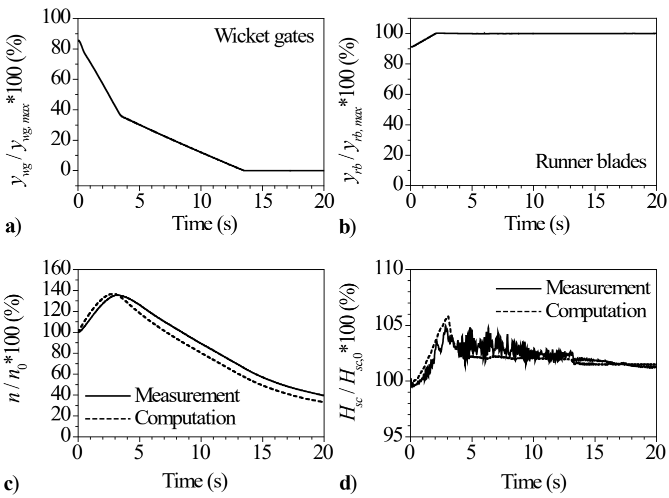

***Figure 6**: Emergency shutdown of the Kaplan turbine unit in Brežice HPP from 21 MW – wicket gate servomotor stroke a), runner blade servomotor stroke b), rotational speed c) and scroll-case pressure head d)*

5 CONCLUSIONS

The main objective of this paper is to identify the most critical normal transient flow regimes that may induce extreme water hammer loads in the Sava River Kaplan turbine hydropower plants. These powerplants are comprised of relatively short inlet and outlet conduits. Therefore, the rigid water hammer model has been used for hydraulic transient analysis. The computational results were compared with the results of measurements in two distinct hydropower plants (HPP): (i) The refurbished and upgraded Medvode HPP, and (ii) The newest Brežice HPP. Water hammer in the two power plants is controlled by appropriate adjustment of the wicket gates and runner blades closing/opening manoeuvres. The agreement between computed and measured results was reasonable.

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Nomenclature

(Symbols)	(Symbol meaning)
A	cross-sectional area
D	runner diameter, diameter
f	Darcy-Weisbach friction factor
G_d	geometric characteristic of the outlet conduit
G_u	geometric characteristic of the inlet conduit
g	gravitational acceleration
H	pressure head, head
H_r	rated net head
H_{sc}	scroll-case pressure head
I	polar moment of inertia
L	length
n	turbine rotational speed
P_r	rated turbine output
Q	discharge
t	time
x	distance
y_{gw}	wicket gate servomotor stroke
y_{rb}	runner blade servomotor stroke
ω	angular velocity

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