DRUGI GODIŠNJI IZVJEŠTAJ MENTORA O NAPREDOVANJU DOKTORANTA

Akademska godina za koju se podnosi izvještaj	2019/2020		
OPŠTI PODACI O DOKTORANTU			
Titula, ime, ime roditelja, prezime	Mr Radislav (Neđeljko) Brđanin		
Fakultet	Mašinski fakultet		
Studijski program	Mašinstvo		
Broj indeksa	1/16		
MENTOR/MENTORI			
Mentor	Prof. dr Uroš Karadžić	UCG, Mašinski fakultet, Crna Gora	Hidro i termo energetika
Ko-mentor	-	-	-

EVALUACIJA DOKTORANDA*					
Koliko ste zadovoljni kvalitetom održanih susreta sa doktorantom?	☐1	☐2	☐3	☐4	**X** 5
Da li je definisan plan rada sa doktorantom?	**X** DA	☐NE			
Da li je doktorand ostvario napredak prema predviđenom planu rada?	**X** DA	☐NE			
Kvalitet napretka doktorantovog istraživačkog rada u periodu za koji se podnosi izvještaj je:	☐1	☐2	☐3	☐4	**X** 5
Ocjena doktorantove spremnosti za konsultacije.	☐1	☐2	☐3	☐4	**X** 5
Ocjena planiranja i izvršavanja godišnjih istraživačkih aktivnosti i stručnog usavršavanja doktoranta.	☐1	☐2	☐3	☐4	**X** 5
Ocjena napretka u savladavanju metodologije naučno-istraživačkog rada.	☐1	☐2	☐3	☐4	**X** 5
Ocjena doktorantovog generalnog odnosa prema studijama.	☐1	☐2	☐3	☐4	**X** 5
Ocjenu ukupnog kvaliteta doktorantovog rada.	☐1	☐2	☐3	☐4	**X** 5

ISPUNJENOST USLOVA DOKTORANDA
Spisak radova doktoranda iz oblasti doktorskih studija koje je publikovao doktorand
1. **Brđanin R.**, Karadžić U., Bergant A., Ilić J. (2019). Recent developments in unsteady pipe flow

*Ocjene su: 1 – nedovoljan, 2 – dovoljan, 3 – dobar, 4 – vrlo dobar, 5 – odličan experimentation at the University of Montenegro. *IOP Conf. Series: Earth and Environmental Science*, Vol.405, doi: 10.1088/1755-1315/405/1/012019

2. **Radislav Brđanin**, Jovan Ilić, Uroš Karadžić, Ivan Božić: *Comparison of dynamic pressure transducers on experimental water hammer setup*, VII Regionalna konferencija: Industrijska energetika i zaštita životne sredine u zemljama jugoistočne Evrope - IEEP '19, 19. - 22. jun 2019., Zlatibor

3. **Radislav Brđanin**, Jovan Ilić, Uroš Karadžić, Ivan Božić: *Experimental water hammer setup at University of Montenegro – description and possibilities*, 14. Međunarodna konferencija o dostignućima u mašinstvu i industrijskom inženjerstvu – DEMI 2019, 24. - 25. maj 2019., Banja Luka

4. Jovan Ilić, Ivan Božić, **Radislav Brđanin**, Uroš Karadžić: *Comparative analysis of the hydropower plant transient processes for various surge tank types and improved guide vanes closing law*, 14. Međunarodna konferencija o dostignućima u mašinstvu i industrijskom inženjerstvu – DEMI 2019, 24. - 25. maj 2019., Banja Luka

Obrazloženje mentora o korišćenju sprovedenih istraživanja u publikovanim radovima

Doktorand, mr Radislav Brđanin je položio sve ispite predviđene planom doktorskih studija. Polazna istraživanja pod naslovom „Eksperimentalna i numerička analiza parametara koji utiču na slabljenje, oblik i fazu talasa pritiska kod hidrauličkog udara“ izložio je 23.09.2019. pred komisijom u sastavu: prof. dr Igor Vušanović, prof. dr Uroš Karadžić, doc. dr Esad Tombarević. Komisija je dala pozitivnu ocjenu polaznih istraživanja, a izvještaj komisije je usvojen na sjednici Senata Univerziteta Crne Gore 28.10.2019. godine.

Doktorska disertacija kandidata mr Radislava Brđanina zahtjeva eksperimentalno istraživanje i obradu podataka, kao i izradu koda za numeričku simulaciju. Doktorand je uspješno završio provođenje eksperimenata u Laboratoriji za energetiku na Mašinskom fakultetu i analizirao jedan dio podataka. Trenutno se provode aktivnosti na izradi numeričkog koda, nakon čega slijedi obrada podataka i poređenje rezultata eksperimenata i numeričke simulacije.

Mr Radislav Brđanin je, kao član radnog tima, učesnik bilateralnog naučno-istraživačkog projekta “Istraživanje i razvoj poboljšanih mera zaštite hidroenergetskih postrojenja pri prelaznim procesima u cilju povećanja njihove pouzdanosti i energetske efikasnosti” koji ima za cilj usavršavanje mladih istraživačkih stručnjaka iz oblasti hidroenergetike i saradnju dvije istraživačke institucije, Mašinskog fakulteta Univerziteta Crne Gore, i Mašinskog fakulteta Univerziteta u Beogradu, i sufinansiran je od strane Ministarstva nauke Crne Gore i Ministarstva obrazovanja, nauke i tehnološkog razvoja Republike Srbije.

Doktorand Radislav Brđanin je publikovao tri rada kao autor i jedan kao koautor u časopisu međunarodnog karaktera i zbornicima konferencija međunarodnog i regionalnog karaktera. Usled epidemije COVID-19, konferencija koja je planirana da se održi u julu 2020. i tom prilikom prezentuje rad **FSI Effects Caused by Electro-pneumatically Operated Ball Valve** - 6th IAHR Europe Congress, June 30th – July 2nd, 2020, Warsaw, Poland (dat u prilogu), pomjerena je za 2021. godinu.

Uzimajući u obzir do sada ostvarene rezultate rada na istraživanju, kao i publikovanje radova,

smatram da doktorand Radislav Brđanin uspješno napreduje ka odbrani doktorske disertacije prema utvrđenoj dinamici.					
Ocjena o aktivnostima sprovedenim na pisanju i objavljivanju naučnih radova.	☐1	☐2	☐3	☐ 4	**X** 5
SAGLASNOST ZA NASTAVAK STUDIJA					
Može li doktorant nastaviti studije?	**X** Da ☐Da, uz određene uslove ☐Ne				
Napomene					
U Podgorici, septembar 2020. godine MP	Ime i prezime mentora Ime i prezime ko-mentora				

- **Objavljeni rezultati rada na izradi doktorske disertacije**

Brđanin R., Karadžić U., Bergant A., Ilić J. (2019). Recent developments in unsteady pipe flow experimentation at the University of Montenegro. *IOP Conf. Series: Earth and Environmental Science*, Vol.405, doi: 10.1088/1755-1315/405/1/012019

Radislav Brđanin, Jovan Ilić, Uroš Karadžić, Ivan Božić: *Comparison of dynamic pressure transducers on experimental water hammer setup*, VII Regionalna konferencija: Industrijska energetika i zaštita životne sredine u zemljama jugoistočne Evrope - IEEP '19, 19. - 22. jun 2019., Zlatibor

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Jovan Ilić, Ivan Božić, **Radislav Brđanin**, Uroš Karadžić: *Comparative analysis of the hydropower plant transient processes for various surge tank types and improved guide vanes closing law*, 14. Međunarodna konferencija o dostignućima u mašinstvu i industrijskom inženjerstvu – DEMI 2019, 24. - 25. maj 2019., Banja Luka

- **Neki od neobjavljenih rezultata rada na izradi doktorske disertacije**

Brđanin R., Karadžić U., Bergant A., Božić I: *FSI Effects Caused by Electro-pneumatically Operated Ball Valve* - 6th IAHR Europe Congress, June 30th – July 2nd, 2020, Warsaw, Poland

Radislav Brđanin: Neki rezultati istraživanja – doktorska disertacija, 2020

Recent developments in unsteady pipe flow experimentation at the University of Montenegro

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Recent developments in unsteady pipe flow experimentation at the University of Montenegro

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Abstract. This paper presents recent experimental results of pressure measurements during filling and emptying of a relatively small-scale pipeline at the University of Montenegro. Experimental setup for investigation of water hammer and its special effects (unsteady friction, cavitation, column separation, trapped air, fluid-structure interaction - FSI), and pipeline filling and emptying is installed at the Faculty of Mechanical Engineering. It consists of an upstream end high-pressurized tank, horizontal steel pipeline (total length: 55.37 m, inner diameter: 18 mm, pipe wall thickness: 2 mm), four valve units positioned along the pipeline including the end points, and a downstream end outflow tank. The setup was upgraded in 2018 with the installation of new piezoresistive pressure transducers and pipe displacement sensors as well as additional electro-pneumatically operated ball valve at the upstream end of the pipeline. The filling of an initially empty pipeline is performed by a sudden opening of the valve positioned at the high-pressurized tank filled with water. The pipeline emptying process is accomplished by high-pressurized air supplied from the air reservoir installed in the air supply line. The high-pressurized tank is closed, and the downstream end valve is opened. Experimental runs have been performed with different initial values of pressure in the upstream end high-pressurized tank (filling) and air supply line (emptying). Results of new pressure measurements are analyzed and commented, with a reference to the previous experiments presented at 6th IAHR WG Meeting in Ljubljana, 2015.

1. Introduction

Rapid filling and emptying of pipes is commonly encountered in water supply and sewer systems, during which pressure transients may cause unexpected large pressure events [1]. Pipeline filling is an essential part of the operation of water systems. In order to avoid large pressure surges, slow filling is usually adopted in engineering applications. However, rapid filling sometimes occurs due to valve failure, which may result in severe transient flows [2]. Emptying pipelines can be critical in many water distribution networks because sub atmospheric pressure pulses could cause considerable damage to the system due to the consequent expansion of entrapped air [3]. Thus, the filling with liquid of an initially empty pipeline and the emptying of an initially liquid-filled pipeline should be investigated both experimentally [3], [4], [5], [6] and numerically [1], [2], [3], [6] in order to ensure accurate prediction of transients in advance and consequently to avoid dangerous events.

This paper presents recent experimental results of pressure measurements during filling and emptying of a relatively small-scale pipeline at the University of Montenegro. Experimental runs have been performed for similar initial conditions as for the experiments presented at 6th IAHR WG Meeting in Ljubljana, 2015 [5]. New results are analysed, commented and compared with previous experiments.

2. Experimental setup

A small-scale pipeline apparatus for investigation of water hammer events including column separation, fluid-structure interaction, unsteady friction, and pipeline filling and emptying has been constructed at the Faculty of Mechanical Engineering [5] and upgraded in 2018. The apparatus is comprised of a horizontal pipeline that connects the upstream end high pressurized tank to the outflow tank (steel pipe of total length L = 55.37 m; internal diameter D = 18 mm; pipe wall thickness e = 2 mm) – figure 1.

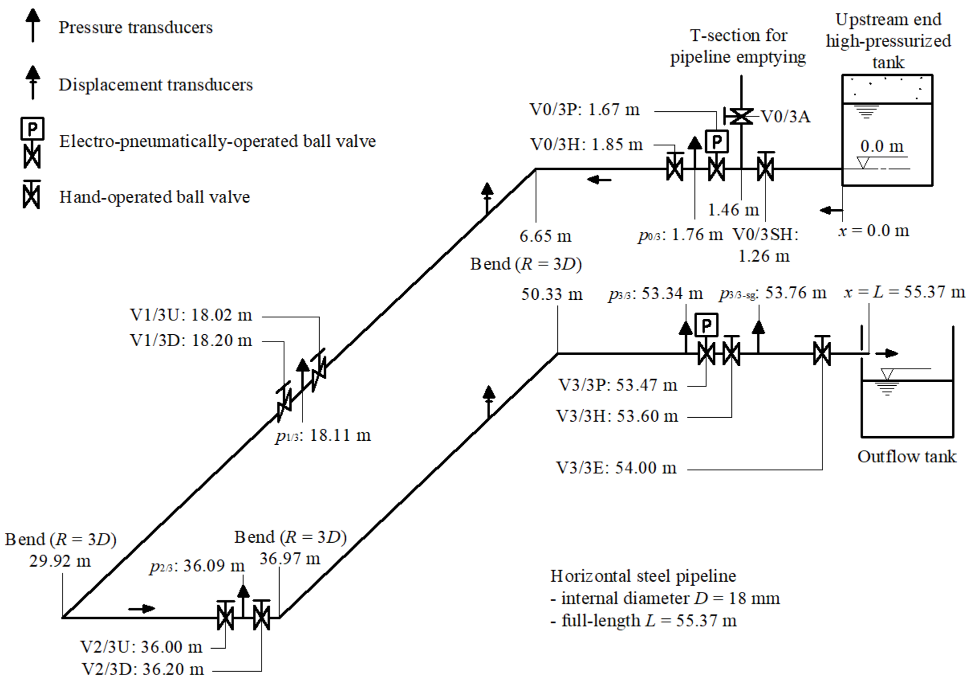

Figure 1. Layout of small-scale pipeline apparatus at University of Montenegro.

Four valve units are positioned along the pipeline including the end points. The valve units at the two tanks (positions 0/3 and 3/3) consist of an electro-pneumatically operated ball valve and hand-operated ball valve. Valve units at the two equidistant positions along the pipeline (positions 1/3 and 2/3) consist of two hand-operated ball valves. All units are connected to the intermediate pressure transducers block. A T-section at the upstream end unit serves for pipeline filling and emptying experiments. There are four bends (90°) on the pipeline with radius $R = 3D$. The pipeline is fixed against axial displacement in 37 points (near the valve units and bends). The air pressure in the upstream end tank can be adjusted up to 800 kPa. The pressure in the tank is kept constant during each experimental run by using a high-precision fast-acting air pressure regulator (precision class: 0.2 %) in the compressed air supply line. The fast closing electro-pneumatically operated ball valves (V3/3P and V0/3P) are controlled with filtered compressed air which is supplied through a plastic pipeline from the pressure regulator, in which the pressure is independent from the rest of the system. The transient event can be triggered by fast closure or opening of the end valves, using either the V3/3P or V0/3P. In addition, transients can be induced by closure or opening of hand-operated ball valves (valves V0/3H, V3/3H and V3/3E; V*i*/3U and V*i*/3D; *i* =1, 2). The hand operated ball valve V3/3E is currently used for adjustment of the initial pipe discharge.

2.1. Instrumentation

Pressures at $p_{0/3}$, $p_{1/3}$, $p_{2/3}$ and $p_{3/3}$ are measured within the valve units along the pipeline including the end points (figure 1). Dynamic pressures are measured by Dytran 2300V4 high-frequency piezoelectric absolute pressure transducers (pressure range: from 0 MPa to 6.9 MPa; resonant frequency: 500 kHz; acceleration compensated; discharge time constant: 10 seconds (fixed)). Due to the fixed time constant (inability to measure very slow varying pressure [5]) four piezoresistive absolute pressure transducers Keller PAA-M5 HB (pressure range: from 0 to 30 bar, sensitivity: 10 mV/0.03 bar, precision ± 0.1%) were mounted next to Dytran transducers in 2018. The datum level for all pressures measured in the pipeline and at the tank is at the top of the horizontal steel pipe (elevation 0 m in figure 1). Two displacement transducers (HBM K-WA-L010W-32K, measuring range: 0 to 10mm, precision ± 0.2%) are placed on their own supports, so they can be moved to different positions along the pipeline. Valves V3/3P and V3/3H are equipped with a fast-response displacement transducer (measurement range: 0° to 90°, frequency response: > 10 kHz) which measures the change of the valve angle (α) during its closing or opening. At the upstream end high-pressurized tank and at the downstream end of the pipeline, two E+H PMP131 strain-gauge pressure transducers ($p_{0/3\text{-sg}}$ and $p_{3/3\text{-sg}}$; pressure range: from 0 MPa to 1 MPa, uncertainty: ±0.5 %) are installed. These transducers are used for the evaluation of the initial conditions in the system. The initial discharge (velocities larger than 0.3 m/s) is measured by the electromagnetic flow meter (uncertainty: ±0.2 %). All measured data are collected by the programmable logic controller (compact DAQ platform by National Instruments) connected to a PC, with software that is also used for control of the two electro-pneumatically operated ball valves.

2.2. Pipeline filling procedure

Procedure for the pipeline filling is as follows. The pressure in the upstream end high-pressurized tank is adjusted to a desired value using a high precision air pressure regulator. The downstream end emptying valve V3/3E is opened to appropriate position. The upstream end service valve V0/3SH is closed. All valves of the four valve units are fully opened. The air inlet valve V0/3A is closed (isolation of the compressed air supply line). The filling of the initially empty pipeline is initiated by quickly opening the valve V0/3SH. When steady state condition is achieved, the final flow velocity (V_f) is measured using an electromagnetic flowmeter.

2.3. Pipeline emptying procedure

The pipeline is emptied using compressed air supplied from the air reservoir connected with a high precision air pressure regulator. The air pressure for the pipeline emptying is firstly adjusted to a desired value with the air inlet valve V0/3A closed (isolation of T-section). All valves of the four valve units and the upstream end service valve V0/3SH are fully opened. The downstream end emptying valve V3/3E is closed and then the high-pressurized tank is isolated from the system by shutting the upstream end service valve V0/3SH. After that the air inlet valve V0/3A is opened. The process of emptying is started by quickly opening the downstream end emptying valve V3/3E.

3. Experimental results

This section presents measured results from pipeline filling and emptying experimental runs with different initial values of the pressure in the high-pressurized upstream end tank (filling procedure: p_{HPT} = 100; 400 kPa) and air supply line (emptying procedure: p_{Air} = 100; 400 kPa). Some results from previous experiments [5] are given for comparison.

3.1. Pipeline filling

Figure 2 presents a comparison of heads at the downstream end of the pipeline (position 3/3 in figure 1) measured by Dytran 2300V4 piezoelectric pressure transducer and by E+H PMP131 strain-gauge pressure transducer. The pressure in the upstream end tank is p_{HPT} = 400 kPa (head H_{HPT} = 39.2 m), the control needle valve is fully opened, and the final flow velocity in the pipe after the filling process is V_f = 2.21 m/s. It can be seen that the E+H transducer, after the filling process is completed, shows the steady state (actual) value of the pressure, which is not the case with the Dytran transducer (step-like pressure pulse). Results in figure 2 are from the experimental setup with control needle valve installed (previous experiments [5]) which acts as an orifice. In recently modified setup the control needle valve was removed and the results from new measurements are given in figure 3.

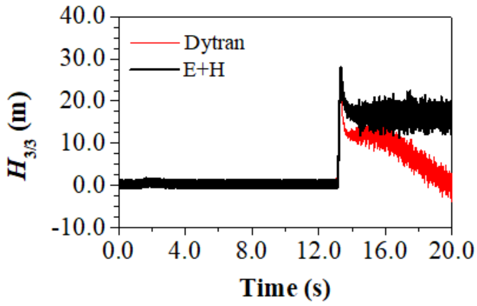

Figure 2. Comparison of heads at the position 3/3 measured by Dytran piezoelectric and E+H strain-gauge pressure transducers: pipeline filling [5].

Figure 3 shows a comparison of heads at positions 1/3 (figure 1), measured by Dytran piezoelectric and Keller piezoresistive pressure transducers, and 3/3 (figure 1), where E+H strain-gauge pressure transducer is added, for the case of pipeline filling with two different values of pressure in the upstream end high-pressurized tank: p_{HPT} = 100; 400 kPa (head H_{HPT} = 11.1; 41.5 m). The downstream end emptying valve is fully open and the final water flow velocity in the pipe is V_f = {1.43; 2.74} m/s for p_{HPT} = {100; 400} kPa, respectively.

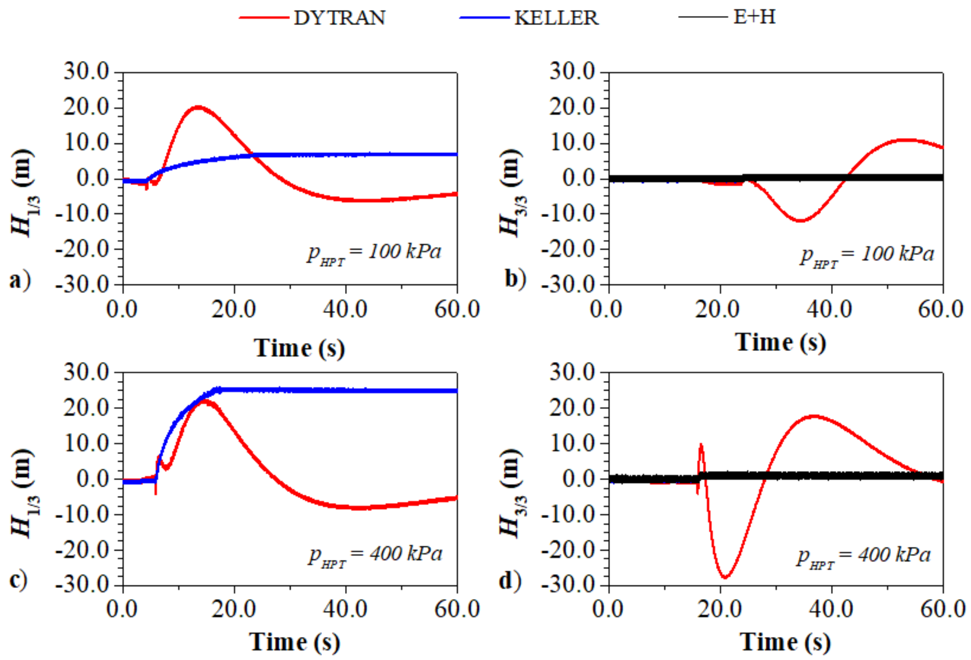

Figure 3. Comparison of heads at positions 1/3 and 3/3 for different initial conditions: pipeline filling.

As it may be seen in figure 3, the removal of the needle valve generates different results. At position 1/3 Keller piezoresistive transducer exhibits smooth pressure rise (ΔH = 7.1; 25.5 m for p_{HPT} = {100; 400} kPa, respectively) much larger than at position 3/3 where only a small head rise may be noticed (ΔH = 0.6; 1.8 m for p_{HPT} = {100; 400} kPa, respectively). Keller piezoresistive transducer shows good agreement with E+H strain gauge pressure transducer at position 3/3, while from comparison at both positions (1/3 and 3/3) it may be seen that Dytran piezoelectric transducer gives inaccurate results due to low discharge time constant which is fixed and it cannot be adjusted.

3.2. Pipeline emptying

Figure 4 shows a comparison of heads at the downstream end of the pipeline (position 3/3 in figure 1) measured by Dytran 2300V4 piezoelectric pressure transducer and by E+H PMP131 strain-gauge pressure transducer. The pressure in the air supply line is p_{Air} = 400 kPa (head H_{Air} = 39.2 m). Again, the results shown in figure 4 are from the experimental setup with a control needle valve installed (previous experiments [5]). New measurements obtained with the control needle valve removed from the setup are given in figure 5.

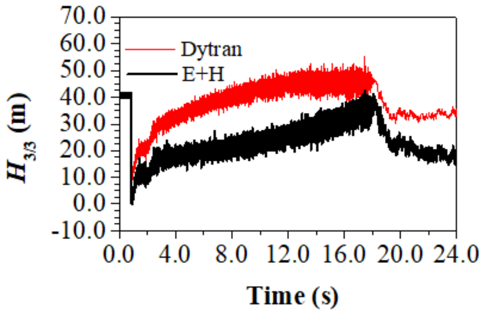

Figure 4. Comparison of heads at the position 3/3 measured by Dytran piezoelectric and E+H strain-gauge pressure transducers: pipeline emptying [5].

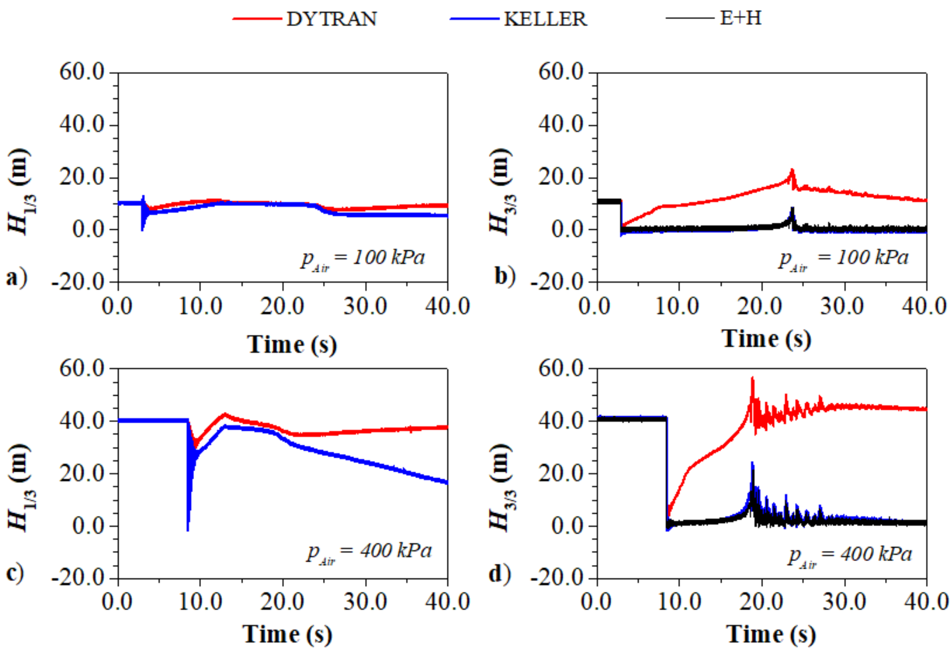

Figure 5. Comparison of heads at positions 1/3 and 3/3 for different initial conditions: pipeline emptying.

Figure 5 depicts comparison of heads at positions 1/3, measured by Dytran piezoelectric and Keller piezoresistive pressure transducers, and 3/3 with E+H strain gauge pressure transducer added, for the case of pipeline emptying with two different values of pressure in the air supply line: p_{Air} = 100; 400

kPa (head H_{Air} = 11.1; 41.5 m). Similarly as for the case of pipeline filling, without the needle valve, different results are obtained for pipeline emptying. At position 1/3, after the V3/3E valve is opened, pressure fluctuations may be noticed. The maximum measured head at position 1/3 (figure 5a) has a higher value (H_{max} = 12.9 m) than the initial head in the air supply line: p_{Air} = 100 (head H_{Air} = 11.1 m). At position 3/3 Keller piezoresistive pressure transducers shows head rise (ΔH = 8.5; 24.4 m for p_{Air} = {100; 400} kPa, respectively) induced by compressed air. Keller piezoresistive and E+H strain gauge pressure transducers show good agreement, as well as Dytran piezoelectric transducer when considering pressure fluctuations during water expulsion by the air column. After the pipeline emptying Dytran piezoelectric transducer gives nearly initial values of the pressure in the pipeline. Due to the nature of pressure pulses, Dytran transducer exhibit better behaviour in the case of the pipeline emptying in contrast to the case of pipeline filling [5].

4. Conclusions

Experimental setup for investigation of water hammer and its special effects, and pipeline filling and emptying has been recently modified including the installation of new piezoresistive pressure transducers and pipe displacement sensors as well as an additional electro-pneumatically operated ball valve at the upstream end of the pipeline. The downstream end control needle valve has been removed from the setup. New measurements show different results in comparison with previous experiments with the control needle valve. The piezoresistive and strain-gauge pressure transducers show good agreement for both cases, pipeline filling and emptying, as well as the piezoelectric transducer when considering pressure fluctuations during water expulsion by the air column for the case of pipeline emptying. Nevertheless, from comparison of all three transducers it may be seen that the piezoelectric transducer behaves inaccurately at very slow varying pressure due to the fixed low discharge time constant.

Acknowledgements

The authors gratefully acknowledge the support of the Ministry of Science of Montenegro and of the Ministry of Education, Science and Technological Development of Republic of Serbia through the project „Research and development of improved measures for protection of hydropower plants during hydraulic transients in order to increase their reliability and energy efficiency“. In addition, the support from ARRS conducted through the project P2-0126 „Transient two-phase flows“ is gratefully acknowledged as well.

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LOGO WILL BE HERE

EXPERIMENTAL WATER HAMMER SETUP AT UNIVERSITY OF MONTENEGRO – DESCRIPTION AND POSSIBILITIES

Radislav Brđanin[1], Jovan Ilić[2], Uroš Karadžić[3], Anton Bergant[4]

Summary: *At the Faculty of Mechanical Engineering, Podgorica, Montenegro an experimental setup for water hammer investigation was developed and constructed in 2011. This setup was upgraded in 2018 with the installation of new pressure and displacement transducers. An additional electro-pneumatically operated ball valve has been installed, which enables simultaneous and accurate time delayed closure and opening of two valves at the two far ends of the pipe system. All measured data are collected by the programmable logic controller connected to a PC, with software that is also used for control of electro-pneumatically operated ball valves. In this way, a modern apparatus with sophisticated equipment has been obtained, where it is possible to conduct precise experiments with unsteady fluid flow and to develop appropriate numerical models and methods of measurement that would have an application on hydropower plants and water supply systems.*
Keywords: water hammer, experimental setup, transducers

1. INTRODUCTION

Water hammer is an extremely complex phenomenon that occurs when the flow regime changes in the flow-passages of hydroelectric power plants and water supply systems. Water hammer causes the formation of waves of high or low pressure which travel through the hydraulic pipe system with a speed close to the speed of sound. These pressure waves, if not controlled in an adequate manner, can lead to malfunctions and even breakdown of the hydraulic system. The side effects of water hammer are unsteady friction, cavitation and column separation, fluid-structure interaction, and visco-elastic effects occurring in pipelines made from plastic materials. Water hammer is usually caused by changing the operating mode of hydraulic turbomachinery as well as by opening and closing of the control and safety valves [2], [5]. The right path for a proper understanding of this complex phenomenon is research

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in strictly controlled laboratory conditions on experimental pipeline apparatus and verification of assumptions adopted in numerical models [3], [6]. The need for having accurate experimental results to verify numerical models is the main reason why the setup described in this paper has been developed and constructed and why there is continuous work on its improvement.

2. EXPERIMENTAL SETUP

A small-scale pipeline apparatus for investigation of water hammer events including column separation, fluid-structure interaction, unsteady friction and pipeline filling and emptying is constructed at Faculty of Mechanical Engineering [1], [4]. The apparatus is comprised of a horizontal pipeline that connects the upstream end high pressurized tank to the outflow tank (steel pipe of total length L = 55.37 m; internal diameter D = 18 mm; pipe wall thickness e = 2 mm) – Fig. 1.

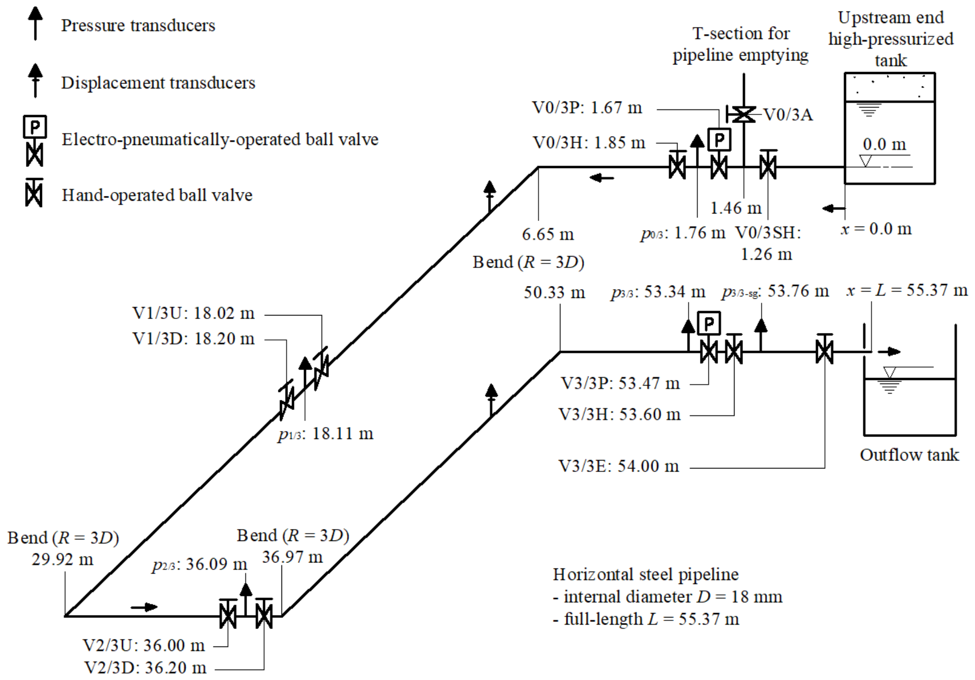

Fig. 1. *Layout of small-scale pipeline apparatus*

Four valve units are positioned along the pipeline including the end points. The valve units at the two tanks (positions 0/3 and 3/3) consist of an electro-pneumatically operated ball valve and hand-operated ball valve. Valve units at the two equidistant positions along the pipeline (positions 1/3 and 2/3) consist of two hand-operated ball valves (valves V*i*/3U and V*i*/3D; *i* = 1, 2). All units are connected to the intermediate pressure transducers block. A T-section at the upstream end unit serves for pipeline filling and emptying experiments. There are four bends (90°) on the pipeline with radius R = 3D. The pipeline is fixed against axial displacement in 37 points (near the valve units and bends). The supports are released when performing FSI effect experiments. The air pressure in the upstream end tank can be adjusted up to 800 kPa. The pressure in the tank is kept constant during each experimental run by using a high-precision fast-acting air pressure regulator (precision class: 0.2 %) in the compressed air supply line. The fast closing electro-pneumatically operated ball valves (V3/3P and V0/3P) are controlled with filtered compressed air which is supplied through a plastic pipeline from the pressure regulator, in which the pressure is independent of the rest of the system. The transient event can be triggered by fast closure or opening of the end valves, using either the V3/3P or V0/3P. In addition, transients can be induced by closure or opening of hand-operated valves along the pipeline (valves V0/3H, V3/3H and V3/3E; V*i*/3U and V*i*/3D; i =1, 2). The hand operated ball valve (V3/3E) is used for adjustment of the initial pipe discharge.

2.1 Instrumentation

Four dynamic and four absolute high-frequency pressure transducers are positioned within the valve units along the pipeline including the end points (Fig. 1). Dynamic pressures at positions $p_{0/3}$, $p_{1/3}$, $p_{2/3}$ and $p_{3/3}$ are measured by Dytran 2300V4 high-frequency piezoelectric absolute pressure transducers (pressure range: from 0 MPa to 6.9 MPa; resonant frequency: 500 kHz; acceleration compensated; discharge time constant: 10 seconds (fixed)) and in addition absolute pressures are measured by Keller PAA-M5 HB (pressure range: 0 ÷ 30 bar, sensitivity: 10 mV/0.03 bar, precision ± 0.1%). The datum level for all pressures measured in the pipeline and at the tank is at the top of the horizontal steel pipe (elevation 0 m in Fig. 1). Two transducers for measuring of the pipe displacement (HBM K-WA-L010W-32K, measuring range: 0-10mm, precision ± 0.2%) are placed on their own carriers, so they can be moved to different positions along the pipeline. Valves V3/3P and V3/3H are equipped with a fast-response displacement transducer (measurement range: 0° to 90°, frequency response: > 10 kHz) which measures the change of the valve angle (α) during its closing or opening. At the upstream end high-pressurized tank and at the downstream end of the pipeline, two strain-gauge pressure transducers ($p_{0/3\text{-}sg}$ and $p_{3/3\text{-}sg}$; pressure range: from 0 MPa to 1 MPa, uncertainty: ±0.5 %) are installed. These transducers are used for the evaluation of the initial conditions in the system. The initial discharge (velocities larger than 0.3 m/s) is measured by the electromagnetic flow meter (uncertainty: ±0.2 %). All measured data are collected by the programmable logic controller (compact DAQ platform by National Instruments) connected to a PC, with software that is also used for control of electro-pneumatically operated ball valves.

2.2 Software

On the PC, connected via the USB port to the PLC, the Lab VIEW-based application *Ispitivanje hidraulickih udara* (*Water hammer investigation*) is installed. The application is used for signal acquisition, valve management, logging of collected data and real-time data display. It is possible to collect data with a frequency from 1Hz to 50000Hz. In the main application window, in the tab *Prikaz sistema* (*System display*), a system diagram showing the pressure, displacement, flow, and valve opening transducers is displayed. The current values are displayed in the indicators. The software also stores data for later processing. From here it is possible to control the opening and closing of the electro-pneumatically operated valves, both manually and automatically. Operator have an option to select the time after which one of the valves will open/close by setting a time delay from 0 ms (the valves will open at the same time) to any other value in ms, which must be divisible by 5 (5ms, 10ms, ..., 1555ms, ...). In the tab *Graficki prikaz* (*Graphical display*) the operator can observe changes in analog signals in real time.

3. EXPERIMENTAL RESULTS

The experimental setup has been tested for a number of steady and transient flow conditions. Experimental runs have been carried out for different initial conditions, pressures in the high-pressurized tank (HPT) and velocities in the pipe system.

In this paper two different experimental tests results are presented, time-delayed closing of electro-pneumatically operated ball valves V3/3P and V0/3P and closing of hand operated ball valve V3/3E at the pipe end.

3.1 Time delayed closure

Fig. 2 shows a comparison of heads at the valve units for the case of time-delayed closure (30 ms) of electro-pneumatically operated ball valves V3/3P and V0/3P. The pressure in the upstream end tank is p_{HPT} = 307 kPa (head H_{HPT} = 31.4 m), the end valve (V3/3E) is fully open, and the flow velocity in the pipe is u_0 = 2.2 m/s.

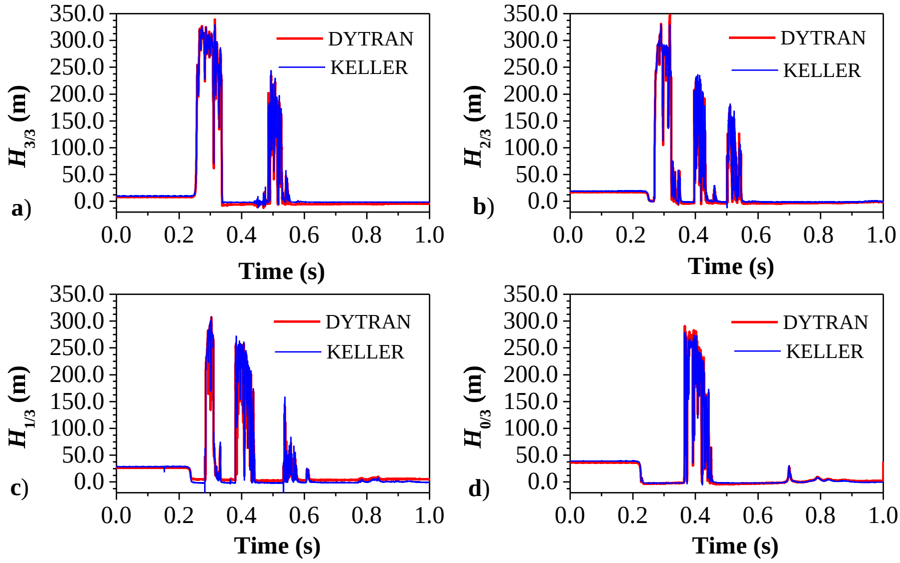

Fig. 2 *Comparison of heads at the valve units (positions $p_{0/3}$, $p_{1/3}$, $p_{2/3}$ and $p_{3/3}$)*

Valve V0/3P is closed first, 30 ms before V3/3P, and what may be seen in Fig. 2d is a pressure drop after the V0/3P valve is closed when the water flows towards the downstream end. That pressure drop is seen also in Figs. 2b and 2c before a pressure wave induced by V3/3P closure arrives. The closure of the V3/3P valve induces the water hammer with cavitation represented by a constant vapour pressure line. Pressure pulsations stop shortly after valves are closed. The maximum head H_{max} = 329 m is measured after the V3/3P valve is closed, at positions $p_{3/3}$ (Fig. 2a) and $p_{2/3}$ (Fig. 2b).

3.2 Manual closure

Fig. 3 shows a comparison of heads at the valve units for the case of manual closure of hand operated ball valve V3/3E. The pressure in the upstream end tank is p_{HPT} = 79 kPa (head H_{HPT} = 8.1 m), the end valve (V3/3E) is fully open, and the flow velocity in the pipe is u_0 = 1.3 m/s.

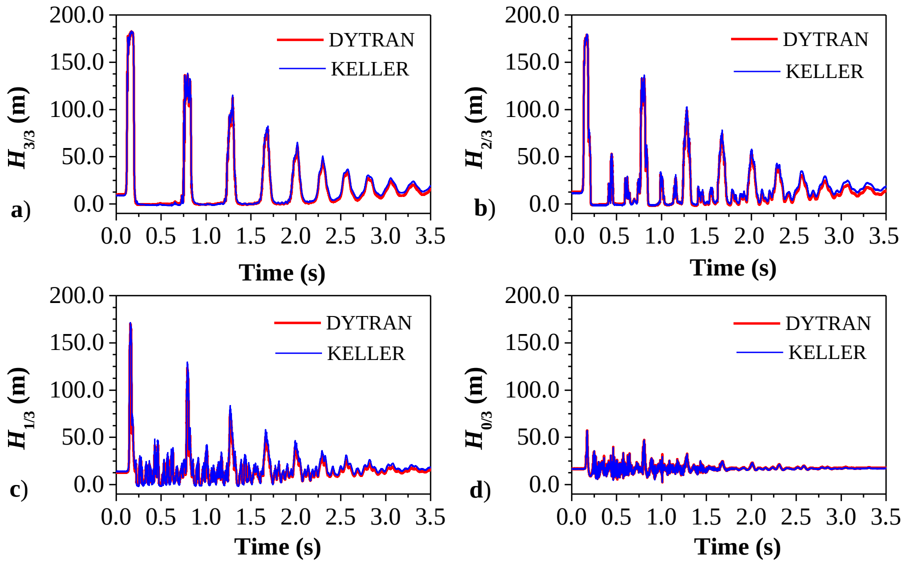

Fig. 3 *Comparison of heads at the valve units (positions $p_{0/3}$, $p_{1/3}$, $p_{2/3}$ and $p_{3/3}$)*

The closing of the V3/3E valve induces the water hammer with transient cavitation (column sparation and distributed cavitation). In cavitation regions along the pipeline, the collapse of vapour bubbles cause small pressure fluctuations. Pressure pulsations last longer than in the previous case. Pressure wave slowly attenuates under unsteady friction effect. The maximum head H_{max} = 182.7 m is measured at the downstream end valve - position $p_{3/3}$ (Fig. 2a), after the V3/3E valve is closed.

Besides these two examples, it is possible to conduct experiments with simultaneous closure of two electro-pneumatically operated ball valves or to produce water hammer events by closing any of the valves at positions $p_{1/3}$, $p_{2/3}$ and $p_{3/3}$, thus changing length of the pipe. Measurements may be undertaken with various values of pressure in the high-pressurized tank to gain experiments with and without cavitation included. In addition, FSI effect experiments are possible when the pipe supports are loosened to inspect Poisson coupling in the pipe straight section or junction coupling when valves or bends are loosened. The setup is also designed for pipeline filling and emptying experiments, as well as experiments with trapped air pockets.

4. CONCLUSIONS

With recent upgrade, a modern setup with sophisticated equipment has been obtained at the University of Montenegro, where it is possible to conduct accurate experiments with unsteady fluid flow and to develop appropriate numerical models and methods of measurement that would have an application on hydropower plants and water supply systems. For the future research, authors are planning to conduct experiments that would include classic water hammer, cavitation and column separation, various FSI effects and simultaneous and time-delayed closure and opening of two valves at the far ends of the pipeline. In this way, a database of experiments for numerical code verification will be created. In addition, the development of a numerical model that would include the elastic water hammer theory, unsteady friction, cavitation and column separation, and fluid-structure interaction effects is also planned. The developed numerical model would be verified by comparison with the obtained experimental results. After its verification, the verified numerical model would be used for the water hammer calculations in real systems.

ACKNOWLEDGEMENT

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FSI Effects Caused by Electro-pneumatically Operated Ball Valve

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ABSTRACT

This paper deals with experimental investigations of the influence of electro-pneumatically operated ball valve (EPV) on fluid-structure interaction (FSI) effect. The experimental setup for investigation of water hammer and its side effects, unsteady friction, cavitation, column separation and FSI is installed at Faculty of Mechanical Engineering, Podgorica, Montenegro. Experimental runs have been performed with different initial values of pressure in the upstream end high-pressurized tank and with EPV fixed and released. Some of the obtained results are presented and conclusions are given.

1. Introduction

Water hammer is an extremely complex phenomenon that occurs when the flow regime changes in the pipelines of hydroelectric power plants and water supply systems. Knowing and describing the phenomena that accompany water hammer (fluid-structure interaction, column separation and unsteady friction) is essential for reliable and safe operation of the plant. The main goal of this paper is experimental research of FSI as a water hammer side effect and the analysis of its impact on the system. The FSI effect is not usually included in water hammer calculations, and its impact can be significant, especially for non-anchored pipelines. The FSI effect calculation is inevitable when it comes to systems that have high security requirements (Tijsseling, 1996). A better understanding of the FSI effect leads to improved pipeline design and reduced possibilities for hydraulic system breakdown (Ferras et al., 2018).

Transient pressures in straight pipelines generate axial stresses and strains in the pipe wall by means of different mechanical processes: the circumferential strain produced by the inner pressure generates an axial strain related with the Poisson effect; the shear stress between the fluid and the pipe wall directly loads the conduit in the axial direction; and finally, unbalanced forces at the points where there is a singularity in the piping system (e.g. in the valve section) load the conduit as well (Ferras et al., 2017). When these mechanisms are large enough to excite and to move the pipe, their effects on the transient pressure wave can be considerable and FSI occurs (Tijsseling, 2007). In this paper, FSI effect occurring due to the movement of the downstream end valve (junction coupling mechanism) is considered.

2. Experimental setup

Experimental setup for investigation of water hammer and its side effects (unsteady friction, cavitation, column separation, trapped air, FSI), and pipeline filling and emptying, is installed at the University of Montenegro, Faculty of Mechanical Engineering. It consists of an upstream end high-pressurized tank (HPT), horizontal steel pipeline (total length 55.37 m, inner diameter 18 mm, pipe wall thickness 2 mm), four valve units positioned along the pipeline with EPVs at the end points, and a downstream end outflow tank.

Four dynamic and four absolute high-frequency pressure transducers are positioned within the valve units along the pipeline including the end points. At the upstream end high-pressurized tank and at the downstream end of the pipeline, two strain-gauge pressure transducers are installed that are used for the evaluation of the initial conditions in the system. The initial discharge is measured by the electromagnetic flow meter. All measured data are collected by the programmable logic controller (PLC) connected to a PC, with software that is also used for control of EPVs.

3. Results and Discussion

Experimental runs have been performed with different initial values of pressure in the upstream end high-pressurized tank, different velocities in the pipe system and with downstream-end EPV fixed and released. In the paper two different experimental tests results are presented; test with EPV fixed (Fig. 1) and test with EPV released (Fig. 2).

Figure 1 shows measured head at the downstream end of the pipeline after fixed EPV is closed (water hammer case). Figure 2 depicts measured head at the downstream end of the pipeline after released EPV is closed (FSI case). In Figs. 1b and 2b first pressure pulse is enlarged. Initial velocity and HPT pressure for both cases are $V_0 = 2.0$ m/s and $H_{HPT} = 21.5$ m, respectively.

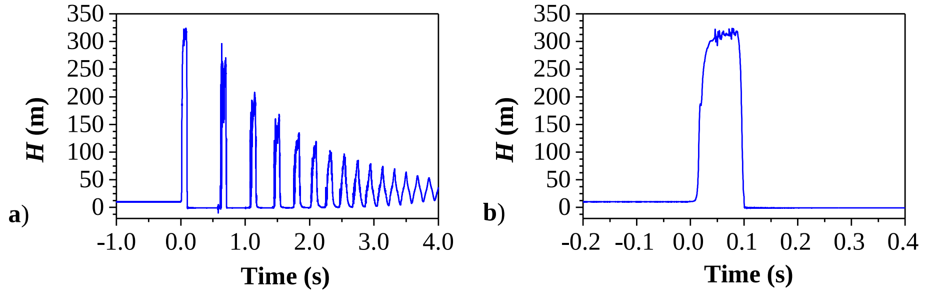

Fig. 1. Measured head at downstream pipeline end – water hammer (WH) case.

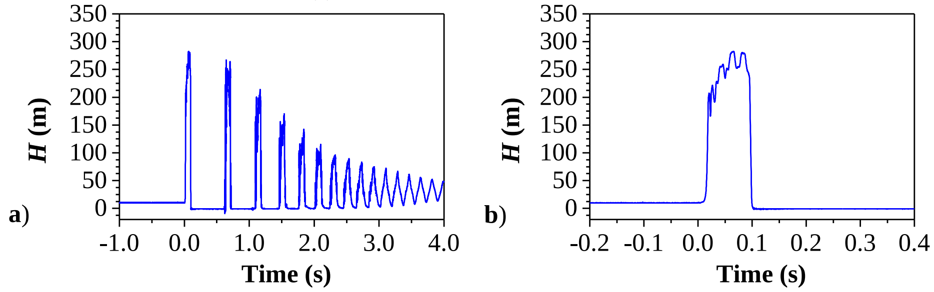

Fig. 2. Measured head at downstream pipeline end – FSI case.

From comparison of obtained results it may be noticed that releasing the valve causes significant FSI effect to occur at the valve position, which leads to a smaller pressure rise ($\Delta H_{FSI} = 272$ m) than for the case of the fixed valve ($\Delta H_{WH} = 307$ m). Occurrence of the FSI effect is evident in Fig. 2b where pressure fluctuations caused by the valve moving are present.

4. Conclusion

Tests conducted on laboratory experimental setup have shown that releasing the EPV at the downstream end causes FSI effect, due to junction coupling mechanism. In the presented cases FSI effect led to a smaller pressure rise than for the case of the fixed valve where pressures are much higher. Also, FSI effect led to a slightly different system behaviour seen through the pressure readings.

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COMPARATIVE ANALYSIS OF THE HYDROPOWER PLANT TRANSIENT PROCESSES FOR VARIOUS SURGE TANK TYPES AND IMPROVED GUIDE VANES CLOSING LAW

Jovan Ilić[1], Ivan Božić[2], Uroš Karadžić[3], Radislav Brđanin[4],

Summary: *Analysis of transient processes is necessary at the design stage as well as during refurbishment of a hydropower plant (HPP). Comprehensive analysis of non-stationary phenomena during transient processes at HPP implies investigation on possible improvements through operation and constructive protection measures. In this paper, the analysis of relevant constructive measures for HPP Pirot is presented comprising the improved tri-linear guide vanes closing law, which can be implemented instead of the current linear one. HPP Pirot is equipped with the two-chamber surge tank and synchronous pressure regulating valves (SPRVs) on the turbines. SPRVs are installed directly at turbines spiral cases, and their opening law is complementary to the closing law of the guide vanes. Prior to analyzing the HPP characteristics during emergency shut down regime for various potential surge tank types, the research of the safety of the existing surge tank with the improved closing law has been conducted for the same operational condition.*

Key words: hydropower plant, transients, surge tank, water-mass oscillations, water hammer.

1. INTRODUCTION

Analyses of transient processes for the extreme operations present prime objective for defining safety elements and secure exploatation of a hydropower plant (HPP) [1]. Although safety is of great importance, detailed research of HPP operation is required to further fullfil techno-economic demands regarding its maximum efficiency. Contemporary refurbishment enables improvement of various HPP characteristics. In general, transients analyses can be done in multiple ways depending on the type of a problem under investigation [2]. In this paper water hammer (WH) and water-mass oscillations (WMO) analyses are conducted by using original

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software that has been developed. WH is based on pressure and discharge variations in the high-pressure part of the derivation system (surge tank – penstock – turbine) to investigate transient behaviour of the penstock system and the turbines. WMO analyses are performed if there is a surge tank within HPP. These transients are manifested by low-frequency pressure and discharge oscillations in the low-pressure section of the derivation system (reservoir – tunnel – surge tank). The WMO analyses of relevant constructive measures for HPP Pirot is presented in the paper comprising the improved tri-linear guide vanes closing law, which can be implemented instead of the current linear one [3].

2. CASE STUDY

HPP Pirot is located in the south-east of Serbia. Upper reservoir is “Zavojsko” lake which has an altitude of 600 masl. Level of the lower water is around 370 masl. HPP “Pirot” is equipped with two Francis turbines of 40 MW each, rotational speed of 500 rpm, and maximum flow up to 45.6 m3/s. This plant has more than eight kilometres of tunnels and around two-kilometre-penstock. Surge tank is placed at the end of the tunnel section. Apart from the previously mentioned, the HPP has additional security elements - synchronous pressure relief valves (SPRVs) which are placed directly on spiral casing (Fig. 1).

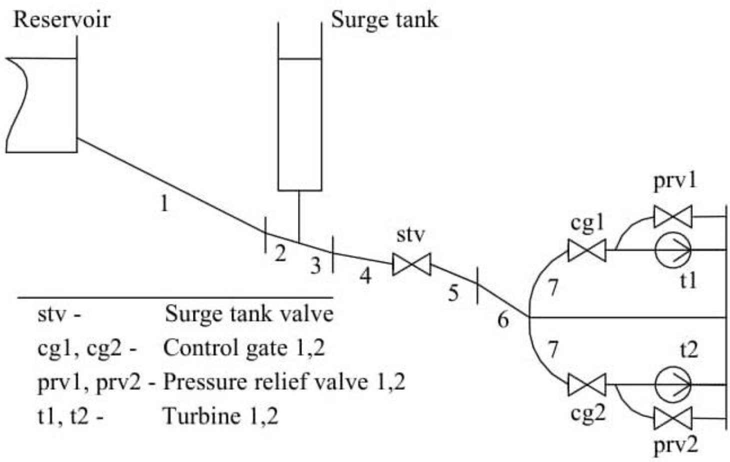

Fig. 1 *Hydropower plant Pirot - scheme[2]*

PRVs are usually coupled with the guide vanes of a hydraulic turbine, which means that law of PRVs openning stroke is complementary to the turbines guide vanes closing stroke. PRVs are needle type valves of 800 mm diamater. Surge tank (fig. 2) is connected to the main waterway by a lateral standpipe. Wave velocity is calculated between 1270 m/s and 1300 m/s in tunnel reach and 800 m/s to 950 m/s in the penstock reaches. Characteristic water elevation of the upper reservoir are as follows: minimum level 568 masl, maximum operating level 615 masl and spill-over level 617.3 masl. Surge tank valve is a butterfly valve of 3000 mm diameter.

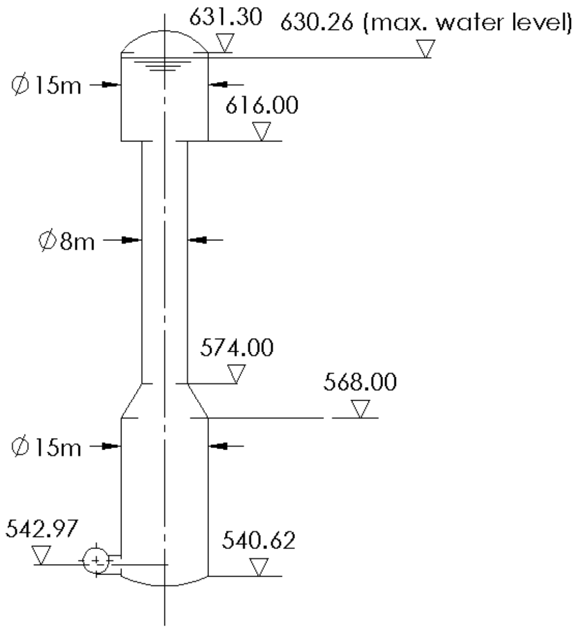

Fig. 2 *Hydropower plant Pirot – surge tank [4]*

2.1 WH ANALYSES IMPROVED GUIDE VANES CLOSING LAW

The main purpose of WH analyses is to appropriately select constructive (for newly designed HPPs – penstock sections diameters and path, flywheel of the generator-unit etc.) and operational (turbine guide vanes closing law - GVCL, pressure relief valve manoeuvring law - PRVML, etc.) protective measures. WH is investigated over a relatively short time frame (up to a few tens of seconds). WMOs, being slow oscillations, are investigated over a relatively long period (a few minutes or tens of minutes). Parameters that are subject to WH analyses are turbine rotational speed (TRS), spiral casing head (SCH) and head envelopes in the derivation system along the waterway path. WMO and WH are investigated by the same mathematical model, whereas the difference is just in the nature of these two processes. Also, different investigated issues and protective measures that should be adopted are based on maximum and minimum acceptance criteria for defined parameters and consider the improvement of the current values.

Former research [3] of GVCL for the HPP included comparison of three different closing law types – linear, bi-linear and tri-linear. The conclusion was that tri-linear (case TL1) GVCL has better performance in TRS and SCH rise. Case TL1 is defined with – up to 40 % closure for 1 sec, up to 20% closure in 3 sec and 10 sec to total closure of the guide vanes. Further research for the improvement of tri-linear GVCL is conducted so that new GVCL (case TL1a) is defined – up to 40% closure in 1 sec, up to 20% closure in 2 sec and total closure in 10 sec. SPRV openning is complementary to the GVCL with closure of 90 sec afterwards (Fig. 3).

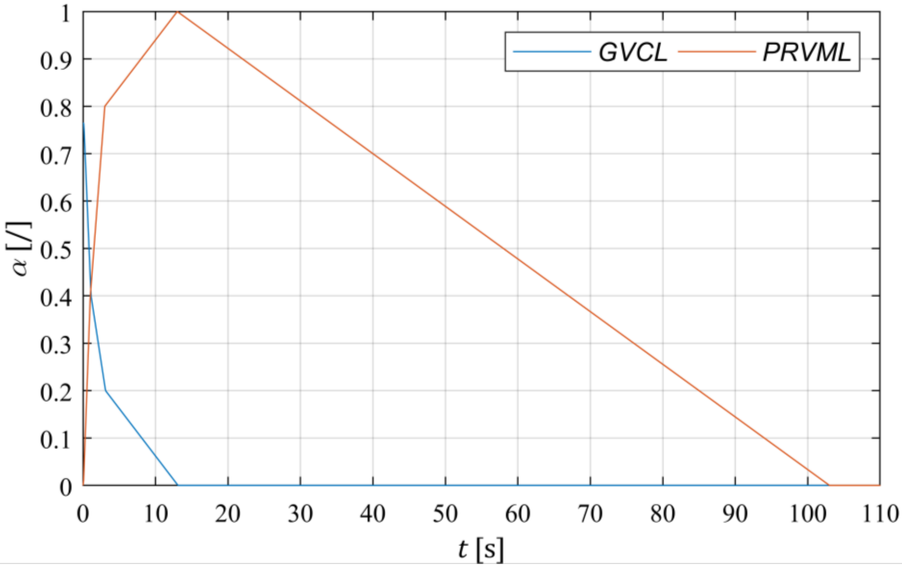

Fig. 3 *Case TL1a - guide vanes closing law and pressure relief valve maneuvering law*

2.2 WMO ANALYSES

Water-mass oscillations analyses are used to investigate an unsteady phenomena in the low-pressure part of the derivation-type HPPs provided with the surge tanks. This system is characterized by low-frequency, slow-changing hydraulic oscillations.

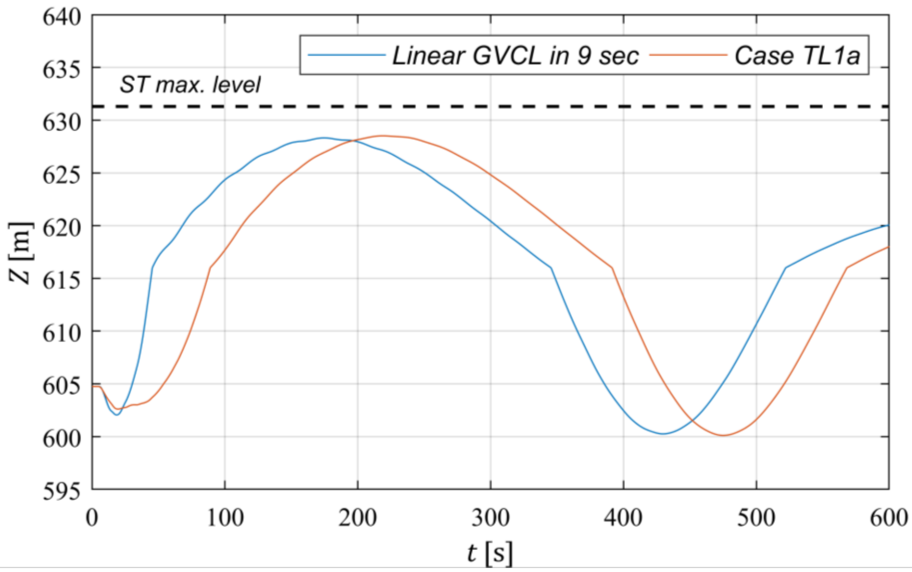

Fig. 4 *STWL for linear in 9 sec and tri-linear TL1a GVCL*

The main purpose of WMO analyses is to appropriately select constructive (surge tank location, type and parameters) and operational (manoeuvring laws) protective measures. Main parameters of these analyses are surge tank water level (STWL), discharge upstream of the tunnel (Qups) and discharge through stand pipe that connects the surge tank with the derivation system (Qsp). Figure 4 shows STWL for the linear GVCL in 9 sec that is currently installed in HPP and newly defined tri-linear GVCL (case TL1a). Although emergency shut down is not the most extreme case of STWL rise [2], it is convenient for comparative analysis.

Surge tank on the HPP is designed with two chambers of 15 m diameter and a core of 8 m diameter, with a stand pipe and orifice (case CVOD_orf_GK15DK15J8).

Table 1 Analyzed surge tank types

Case	*Type*	D_{st} [m]	D_{upper_ch} [m]	D_{lower_ch} [m]
CVOD	*Cylindrical surge tank*	*17*	/	/
CVOD_orf	*Cylindrical surge tank with orifice*	*13.5*	/	/
CVOD_orf_GK155DK13J7	*Cylindrical surge tank with chambers and orifice*	*7*	*15.5*	*13*
CVOD_orf_GK15DK15J8	*Cylindrical surge tank with chambers and orifice*	*8*	*15*	*15*

Comparative analyses of different surge tank types with the dimensions that may be acceptable when considering HPP's design (Tab 1) have been conducted within this research. Defined surge tank types present basic types that are usually implemented on the HPPs.

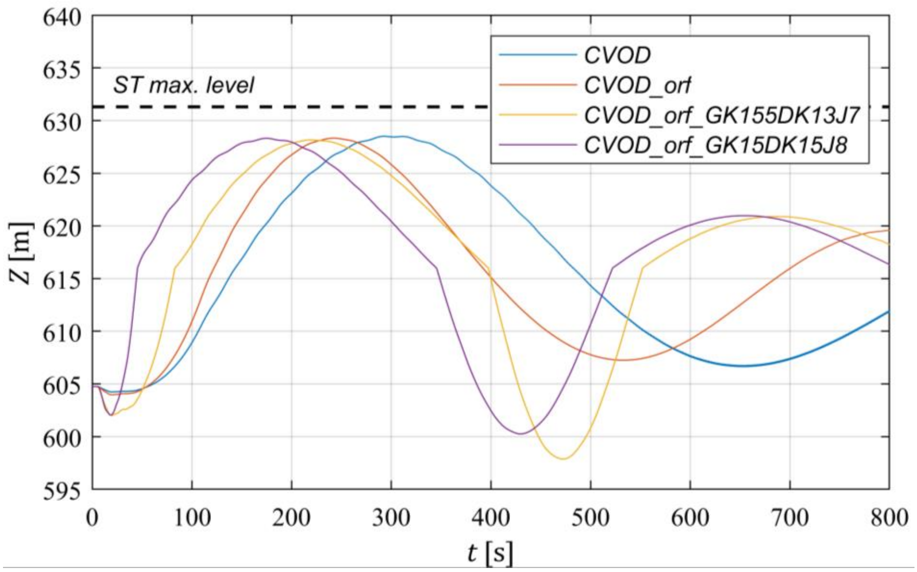

Fig. 5 *STWL for TL1a GVCL for different surge tank types*

Results of the analyses at emergency turbines shut down with TL1a GVCL are presented in Fig. 5 for different surge tank types. Parameter of the investigation is the surge tank water level (STWL). It is illustrated that all defined surge tank types are correctly chosen for the maximum values of the water level. Surge tank maximum level (acceptance criteria) is 631.26 masl and for all surge tanks adequate reserve space is taken into account in case of quick shut-downs [2].

Results of the analyses for turbines simultaneous start are presented in Fig. 6. Minimum acceptance criteria of 544.6 masl is chosen considering derivation system level on the installed location to prevent air suction. Simultaneous quick start as the most extreme case for minimum STWL is taken into account with expected values.

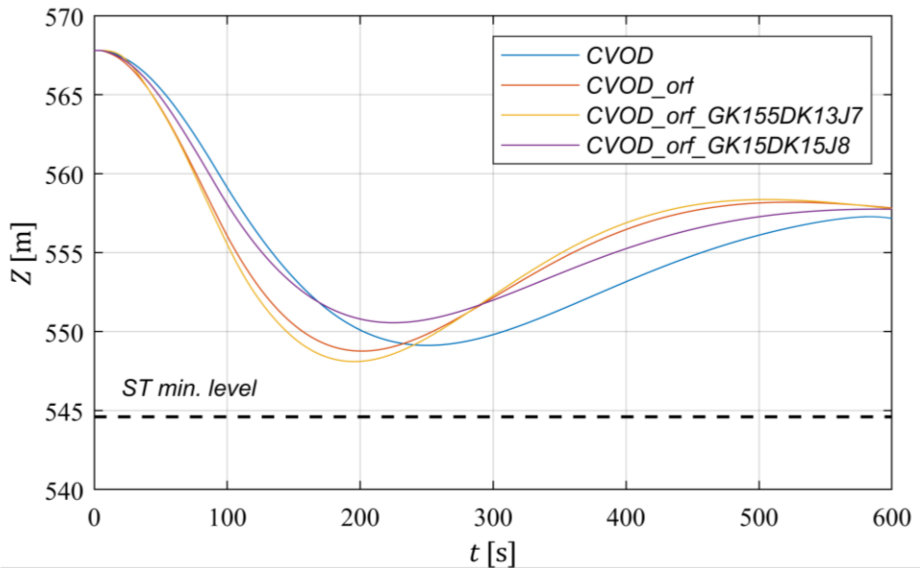

Fig. 6 *STWL for 90 sec simultaneous start for different surge tank types*

3. DISCUSSION

Comparison of the existing and newly defined GVCL through WMO analyses shows that the tri-linear GVCL may be implemented and have no unexpected effects on the derivation system.

In case CVOD, a cylindrical surge tank is considered. Research is conducted for different diameter values and the minimum one that satisfies acceptance criteria is 17 m.

Further on, case CVOD_orf takes into account the setting of the orifice. Results show that implementation of the orifice reduces surge tank diameter to 13.5 m which is a significant difference having in mind techno-economic analysis. The idea of implementing orifice lies in its local resistance but it should be carefully chosen as it may have effect on the water hammer reflection and efficiency may be diminished.

Case CVOD_orf_GK15DK15J8 defines existing surge tank construction parameters and results indicate best performance. Surge tank is equipped with the orifice, the lower chamber of 15 m, the core of 8m and the upper chamber of 15 m diameter and height differs for the defined sections (fig. 2).

According to the results, further research is based on a diameter change of the two-chamber surge tank with the idea of optimising construction parameters. Case CVOD_orf_GK155DK13J7 proves that with slightly greater upper chamber of 15.5 m, surge tank may have lower chamber of 13 m and the core of 7 m diameter with parameters within acceptance criteria. All defined types must be a subject of comprehensive analyses to confirm that their construction is possible. The following investigation should be on the quick shut-down and quick start as the most extreme cases for STWL. Sequential turbine starts [5] may also have an effect on reducing the surge tank dimensions with the adverse effect of lower maneuvering capabilities of the HPP.

Developed software also has a possibility of modelling surge tank with overflow, but it is not a subject of this research because volume of the water that is ejected is not easily defined and requests better understanding of the field topology.

4. CONCLUSION

Transient analyses are necessary both during HPP design and refurbishment. Thorough investigation on possible operation and constructive protection measures is the key to succesfully secure HPP but also to reduce unnecessary expenses.

Although analytical methods are often used, they are mostly limited to cylindrical surge tanks as constructive protection measure and what is more important, they are not capable of determining the right operational measures due to the lack of the information on the main parameters. Numerical analyses overcome the analytical ones in many ways and allow for wider approach through modelling of various different protective measures.

Generally, further analyses should be based on modelling various differential surge tanks and analysing their capabilities. Also, it is necessary to conduct a research to improve the existing surge tank types and to develop novel designs from the point of view of increasing HPP reliability and energy efficiency.

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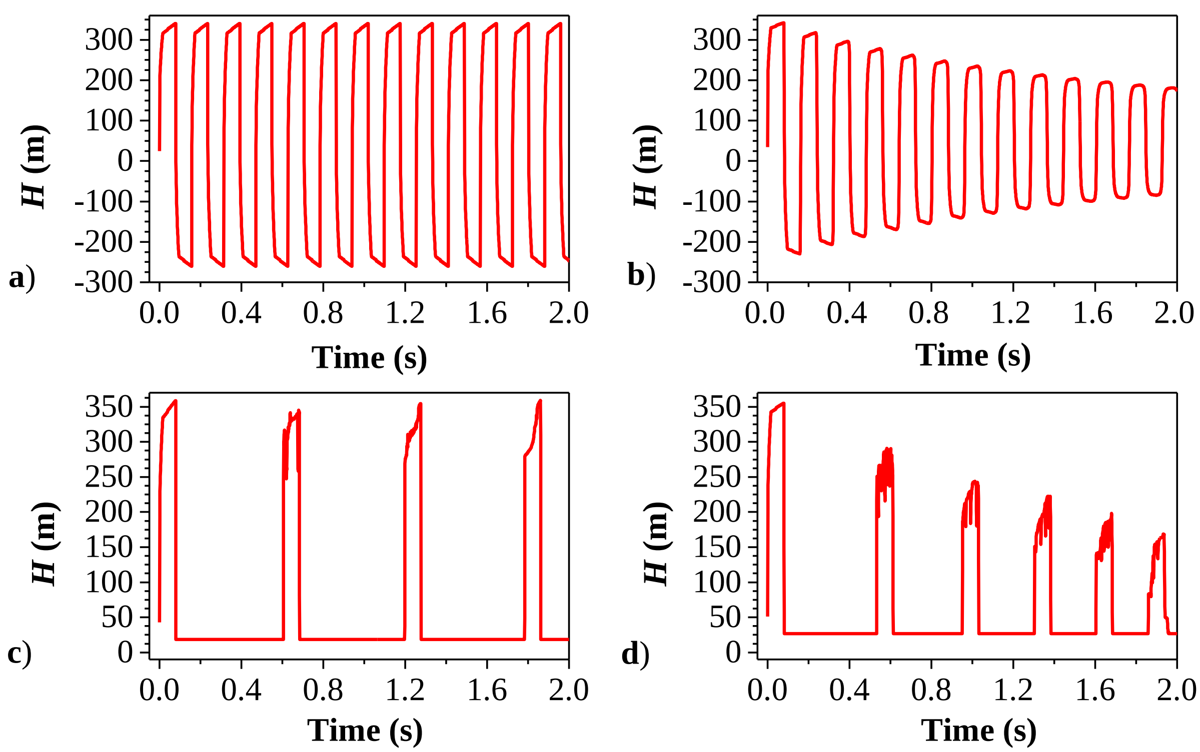
NEKI REZULTATI ISTRAŽIVANJA – DOKTORSKA DISERTACIJA

U ovom dokumentu ukratko su prikazani neki rezultati istraživanja, u okviru izrade doktorske disertacije doktoranda Radislava Brđanina, dobijeni izvođenjem eksperimenata u Laboratoriji za energetske procese, kao i izradom numeričkog koda za simulaciju pojava koje su predmet istraživanja. Takođe, dato je i poređenje eksperimentalnih i rezultata simulacije.

- **Rezultati numeričkog koda**

Na slici 1. dati su rezultati simulacije, odnosno numeričkog koda koji simulira pojavu hidrauličkog udara, kavitaciju i nestacionarno trenje. Slika 1.a) prikazuje simulaciju klasičnog hidrauličkog udara, bez uključenih ostalih efekata, gdje kroz vrijeme ne dolazi do promjene talasa pritiska. Slika 1.b) pored hidrauličkog udara uključuje i nestacionarno trenje, što se primjećuje kroz slabljenje talasa pritiska i blagu promjenu u fazi. Na slici 1.c) uz hidraulički udar uključena je pojava kavitacije i razdvajanja toka, gdje dolazi do velikih promjena u fazi talasa pritiska, kao i u njegovom intenzitetu. Slika 1.d) uključuje oba fenomena, i kavitaciju i nestacionarno trenje, pored hidrauličkog udara, gdje se opet može uočiti promjena faze, slabljenje talasa usljed trenja i sl. Dobijeni rezultati pokazuju mogućnost koda da simulira pojave koje su predmet istraživanja, kako pojedinačno, tako i u različitim kombinacijama, što je i cilj rada.

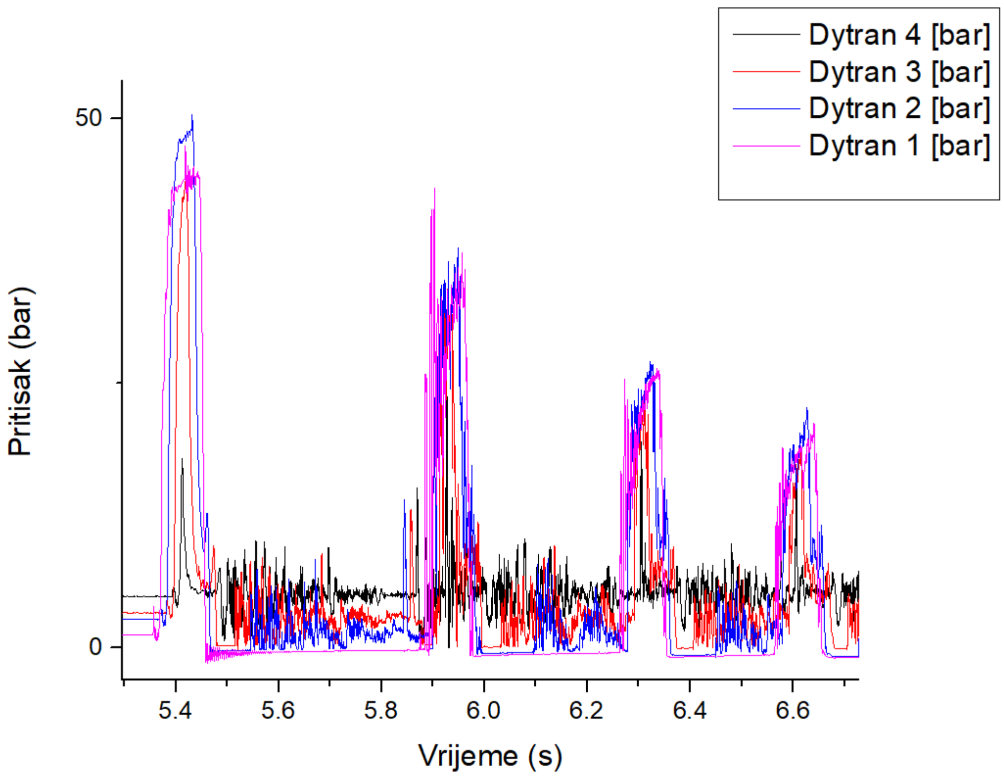


Slika 1. Rezultati numeričke simulacije

- **Rezultati eksperimenata**

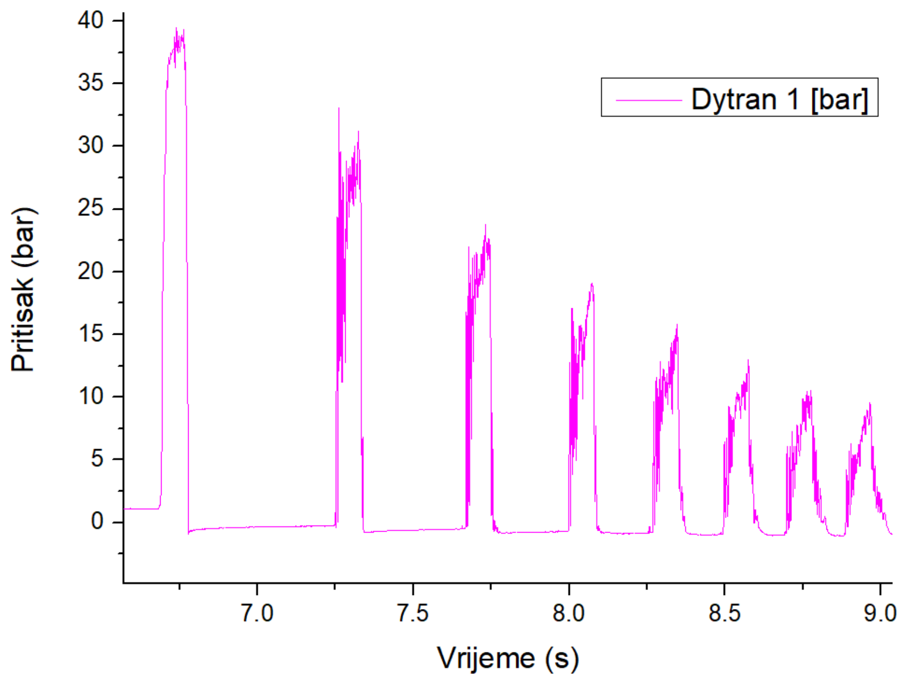
Na sljedećim slikama prikazani su rezultati eksperimenata u laboratoriji koji uključuju pojavu hidrauličkog udara, kavitacije, nestacionarnog trenja i interakciju fluida i strukture.

Slika 2. prikazuje rezutate mjerenja pritiska na različitim pozicijama duž cjevovoda senzorima Dytran, za pritisak u rezervoaru 4bar i brzinu u cjevovodu 2.81 m/s, za slučaj brzog zatvaranja elektropneumatskog ventila na kraju sistema. Dati eksperiment pored izazivanja hidrauličkog udara, uključuje pojavu kavitacije i nestacionarnog trenja.



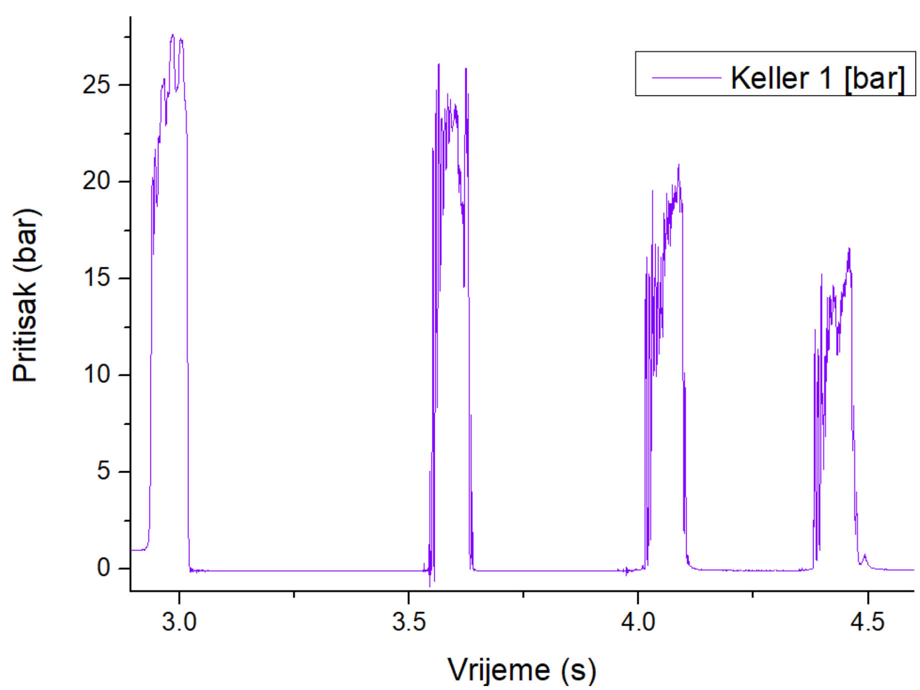
Slika 2. Rezultati eksperimenta HU

Na slici 3. izdvojen je rezutat mjerenja pritiska na samom kraju cjevovoda senzorom Dytran, za pritisak u rezervoaru 3bar i brzinu u cjevovodu 2.33 m/s, za slučaj brzog zatvaranja elektropneumatskog ventila na kraju sistema. Na slici se jasno može uočiti pojava hidrauličkog udara, kavitacije i razdvajanja toka, raspada kavitacionih mjehurova i nestacionarnog trenja.



Slika 3. Rezultati eksperimenta HU

Slika 4. prikazuje rezutat mjerenja pritiska na samom kraju cjevovoda senzorom Keller, za pritisak u rezervoaru 2bar i brzinu u cjevovodu 1.99 m/s, za slučaj brzog zatvaranja elektropneumatskog ventila na kraju sistema.



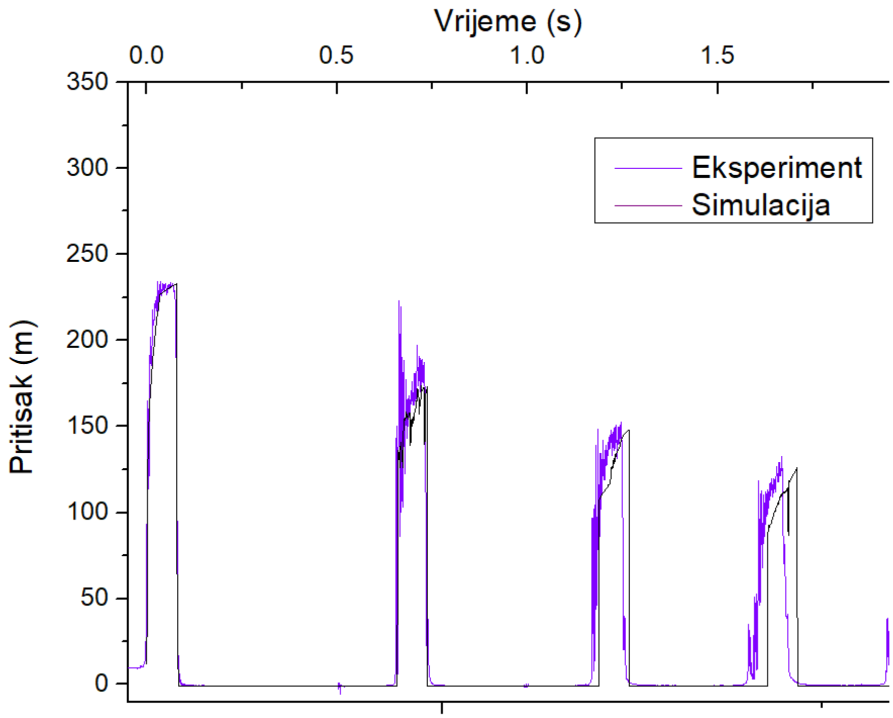
Slika 4. Rezultati eksperimenta FSI

Dati eksperiment pored hidrauličkog udara, uključuje pojavu kavitacije i nestacionarnog trenja i interakcije fluida i strukture (FSI). Na slici se jasno može uočiti pojava FSI efekta na samom početku procesa, kada je on i najdominantniji.

Prikazani rezultati pokazuju da su izvedenim eksperimentima dobijena mjerenja koja obuhvataju sve pojave koje su predmet istraživanja u radu, te stoga omogućavaju njihovu analizu i verifikaciji rezultata simulacije, što je i cilj rada.

- **Poređenje dobijenih eksperimentalnih i rezultata simulacije**

Na slici 5. predstavljeno je poređenje rezutata mjerenja pritiska na samom kraju cjevovoda senzorom Keller, za pritisak u rezervoaru 1bar i brzinu u cjevovodu 1.45 m/s, za slučaj brzog zatvaranja elektropneumatskog ventila na kraju sistema sa rezultatima simulacije razvijenog numeričkog koda. Može se utvrditi da za dati slučaj rezultati simulacije odgovaraju rezultatima eksperimenta kada je u pitanju maksimalna vrijednost pritiska, a relativno dobro i kada je u pitanju faza i slabljenje talasa pritiska.



Slika 6. Poređenje rezultata eksperimenta i simulacije