HYDRAULIC TRANSIENTS IN HYDROPOWER SYSTEMS: FROM THEORY TO PRACTICE

BY DAVID FERRAS, GIOVANNI DE CESARE, DIDIA I.C. COVAS & ANTON J. SCHLEISS

What do we know about transients in hydropower conduits?

Hydropower conduits may be engineered to perform either unpressurized (free-surface) or pressurized (without free-surface). Not only regime transitions and two-phase flows, but also hydraulic transients with associated phenomena, such as fluid-structure interaction, unsteady friction, cavitation or mass oscillation imply strong limitations and uncertainty to water conduits design and operation. Engineers have to be able to identify, to distinguish and to assess the relevant phenomena not accounted for in classic hydraulics, as these may be the cause of ill-defined calculations and subsequent operation problems. Our mission as researchers on the engineering and technology field is to develop and provide the right tools to enhance and empower engineering designs.

Hydraulic transients in pressurized flows is an active research area at the Laboratory of Hydraulics and Environment (LHE) of the Instituto Superior Técnico (IST) in Portugal and the Platform of Hydraulic Constructions (PL-LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. Both institutions have been working jointly over the past 10 years for the enhancement of the fundamental theory and its applicability to real engineering problems in the field of hydropower. The highlights of this collaboration are described hereby.

Fluid-structure interaction and the extended water-hammer theory

The origin and development of the classic water-hammer theory is based on the fact that during unsteady pressurized flows the fluid and the piping structure behaviors are interconnected. In Fluid-Structure Interaction (FSI) all the potential pipe vibration modes that may affect the water-hammer wave propagation are considered and the two-way coupling between fluid dynamics and structural mechanics is described. It is a reasonable assumption to consider that, in common pipe systems, up to eight degrees-of-freedom or pipe vibration modes may be excited under unsteady flow conditions [1]. Large hydropower conduits though are slender single elements and, if their junctions are aligned with the flow direction, axial vibrations outweigh other eventual vibration modes. Consequently, the description of the dynamic interaction between the water-hammer waves in the fluid with the axial stress waves in the pipe-wall is of primary importance in such systems [2].

Experimental and numerical work, using an in-house MoC (method of characteristics) code, has been carried out at LHE (IST) and PL-LCH (EPFL) aiming at investigating the behavior of pipelines constrained against longitudinal movement using pipe supports, anchorages and thrust blocks. In [3], for instance, a robust and accurate MoC code for both the fluid and the structure to simulate anchoring blocks taking into account their inertia and dry friction was presented. The blocks were nested in the numerical scheme as internal conditions, for which junction coupling was considered. Figure 1 shows the experimental pipe rig used to test different pipe anchoring setups on the basis of the classical reservoir-pipe-valve system in which the downstream valve is rapidly shut-down. The validation of the numerical model is shown in Figure 2, where measured *vs.* computed pressures next to the downstream

Figure 1. Experimental pipe rig assembled at LHE (IST) used for FSI analyses in straight pipes [2].

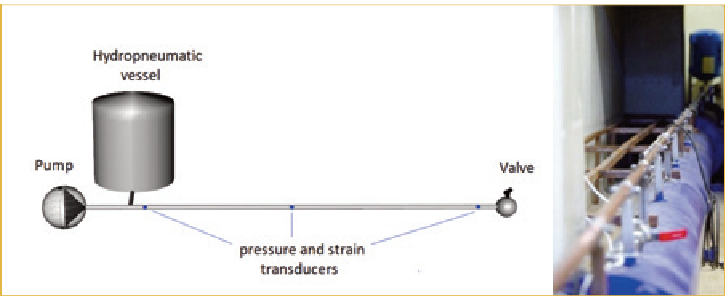


Figure 2. Validation of the numerical model developed in [3] for: anchored pipe ends (a); non-anchored downstream end (b); and non-anchored downstream end but anchored midstream (c).

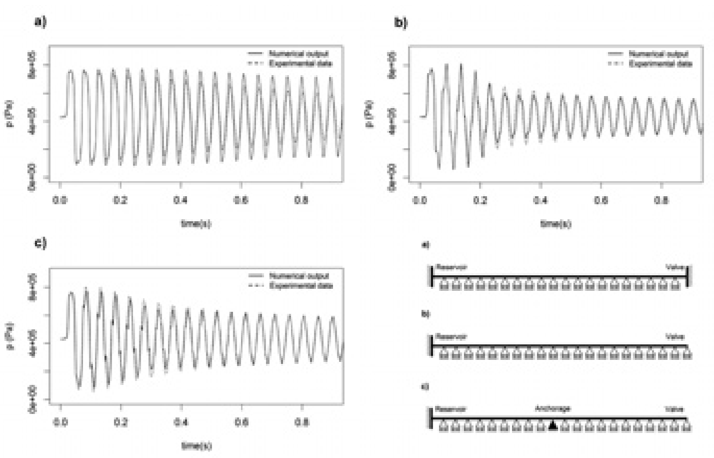
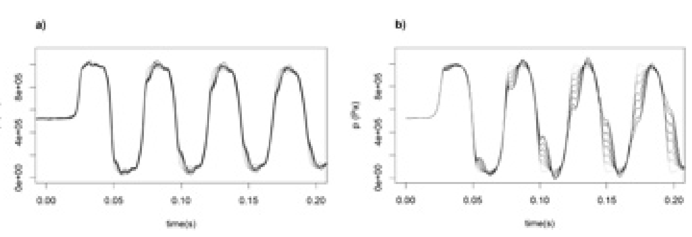


Figure 3. Series of water-hammer tests while releasing the conduit anchorages from the downstream to the upstream pipe ends from: experimental measurements (a); and numerical output (b) [3].



valve are depicted. The model proved to be more accurate when the pipe was not anchored (Figure 2-a). The research suggested that the pipe support effect, dry friction dissipation and the associated assumptions (*e.g.* stick-slip instability) have to be considered when aiming at accurate descriptions of water-hammer events in hydropower conduits. When incorporating FSI there is a substantial increase of computational effort in the numerical simulations. For certain setups though (e.g. valve released) maximum pressures, wave shape and damping are highly altered, hence FSI computation becomes justified.

In [3] the model was also tested and validated using insightful series of experimental tests consisting of releasing, from downstream to upstream and one at a time, the pipe anchorages of a conduit initially fully anchored while launching water-hammer events. Figure 3 depicts both experimental measurements and numerical output, depicting the same trend in the pipe response while anchorages are being released. The numerical implementation proved therefore to be consistent with the empirical data, confirming that the main fluid-structure interaction phenomena is well described by the modelling assumptions.

The research brought valuable insight to the importance of considering FSI phenomena in the engineering designs of straight pipes affected to longitudinal movement, as maximum transient pressures may surpass the ones expected by the classical theory (Joukowsky pressure pulse), while the water-hammer wave damping and timing may be also affected by the dynamic response of the overall structure. A novel, accurate and efficient numerical model that enables the description of the FSI effects of anchoring blocks when considering their resistance to movement due to both inertia and dry friction was successfully developed aiming at providing engineers with a useful tool for improved hydropower conduit designs.

Experimental and CFD modelling of entrapped air during transients events

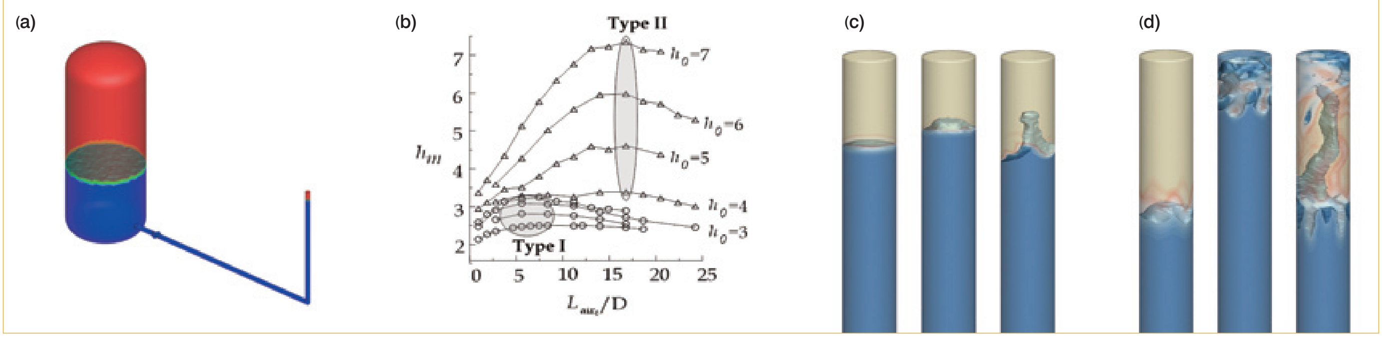
Gases naturally accumulate in pressurized pipes transporting liquids due to inadequate design or operation of valves or pumps, the rapid depressurization and pipe filling after a disruption or the occurrence of transient events [4]. Air is typically entrapped in higher elevation pipe locations or sections with valves and fittings and in quasi-horizontal pipes. The air tends to be accumulated and released by air valves, if they exist and adequately operate. Air pockets create additional losses during normal operation and introduce significant changes in the dynamic response of the liquid-pipe system during transient events. Severe transients combined with entrapped air are responsible for numerous accidents in pressurized pipes. Air pocket volumes are quite difficult to determine, even when using direct pressure measurements. The aim of the research carried out at IST consisted of analyzing the effect of entrapped air in the pressure wave signal during the occurrence of fast transient events both by experimental and CFD modelling for the rapid pipe filling [5] and by experimental analysis for the occurrence of a fast-transient in pipe system with entrapped air [6].

The first tests focused on the rapid pipe filling. A pressurized system, composed of a “tank–pipe–valve–pipe-dead end” (Figure 4-a), was used. Pipes were made of polyvinyl chloride (PVC) and with an inner diameter of 0.0536 m. The pressurization source was a 1 m^3 steel air vessel. The valve that connected the air vessel to the pipes, a quarter-turn ball valve pneumatically actuated, was initially closed and, then, opened in 0.23 s, creating an upsurge at downstream that compressed the air pocket. The initial air pocket size varied for each transient test. In addition to the experimental tests a 3D-VOF model in CFD was developed and used to simulate the rapid filling, since the maximum transient pressures were higher than those that the facility could sustain, putting at risk the pipe system. The model was calibrated and validated using collected data. Based on the CFD model and using the Joukowsky pressure rise as a reference, the dimensionless maximum transient pressures, h_m, were determined for different air pocket sizes, L_{air}/D, and initial differential pressures, h_0 (Figure 4-b). Maximum pressures attained for each pressure difference created, h_0, and the respective volumes are depicted in Figure 4-b with the ellipse shaded area. Two different types of behaviors of the water-air system were observed: Type I in which air and water do not mix and Type II in which air mixes completely in water (Figure 4-c,d).

The second set of tests was carried out in the experimental pipe-rig depicted in Figure 1, where an acrylic device was assembled to simulate the air pocket inside the pipe and installed at the pipe mid-length (Figure 5). This device has a cylindrical hole with an inner diameter of 5 mm and a total drilled length of 51 mm; it has a lateral inlet at 25 mm from the bottom to control the air pocket volume between each test. Transient tests were carried for eight flow rates ranging from laminar to smooth-wall turbulent flow, with a pressure acquisition frequency of 1 kHz during 5 s. Each initial flow rate was tested with five initial air pocket volumes and for the no-air pocket situation.

Several features are identified in the transient pressure signal analysis. First, a major pressure drop is observed in the pressure transducer near the downstream valve after the Joukowsky overpressure is generated. This drop is created by the air volume compression and subsequent expansion. A series of reflected pressure waves are created. The pressure drop increases with the size of

Figure 4. (a) Rapid pipe filling system with trapped air (water=blue; air=red); (b) Maximum pressure and critical air volumes. Air dynamic behavior (c) Type I and (d) Type II [5]



the air pocket for the same initial flow rate (Figure 6-a) and with the initial flow rate for the same initial air pocket size [6]. Second, an overpressure higher than the Joukowsky pulse is observed. After the initial compression, the air pocket starts the compression-expansion cycle. As this cycle is slower than that of the propagation of the main pressure wave in the pipe, maximum overpressures at the downstream end pressure transducer are not reached in the first wave cycle but in the second cycle after the air pocket expansion (Figure 6-b). These overpressures can be as high as 30% of Joukowsky's pressure variation. Thirdly, air pockets also contribute to higher damping of transient events due to the massive energy dissipation in successive compression and expansion of the air, this damping increases with the air pocket size due to the energy dissipation in the compression and expansion of the air cavity [6]. Some combinations might have a resonance effect due to the superposition of pressure waves, which should also depend on the air pocket position in the pipe.

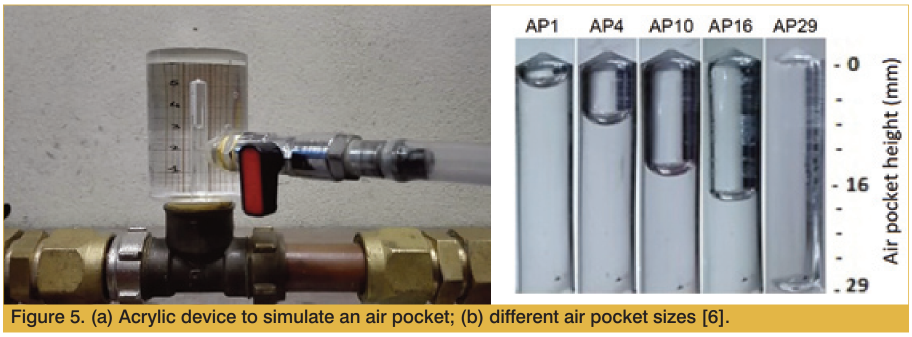


Figure 5. (a) Acrylic device to simulate an air pocket; (b) different air pocket sizes [6].

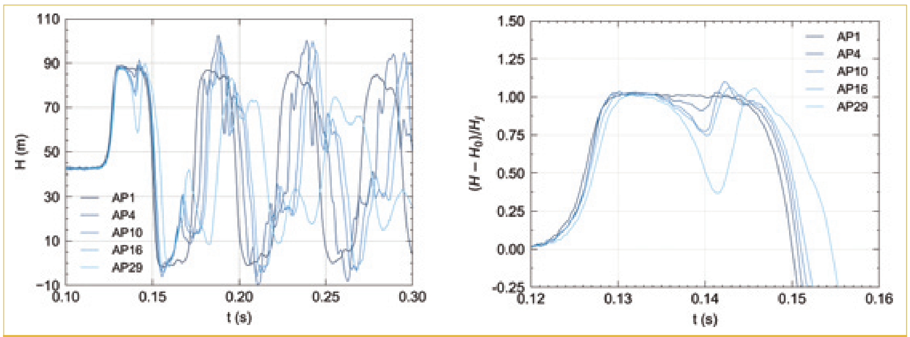


Figure 6. (a) Pressure wave signal and (b) dimensionless transient pressure data collected for five analyzed air pockets situations and initial flow rate Q= 400 l/h [6].

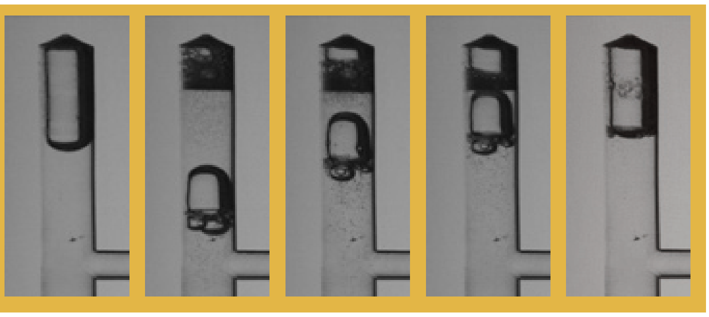


Figure 7. High-speed camera pictures of entrapped air during a hydraulic transient event.

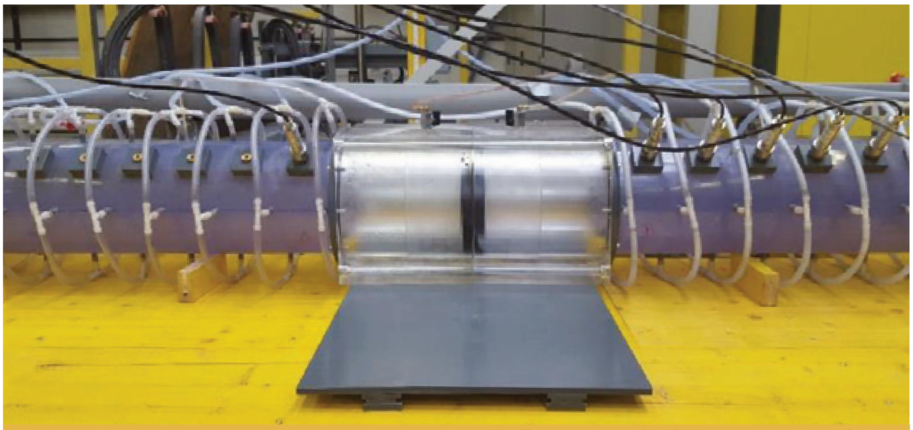
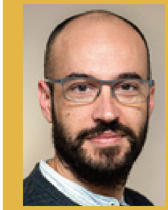


Figure 8. Experimental set-up for the systematic testing of different types of orifices with reversible flow direction.

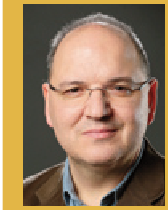
Experimental tests carried out at IST were used to analyse the effect of an air pocket volume in the transient pressure signal. Several initial flow rates for five entrapped air volumes were tested. Four pressure wave features were analyzed: initial pressure wave drop, maximum observed overpressures, pressure wave damping and phase shift. The pressure drop was higher for larger initial air pocket volumes. Maximum overpressures had a maximum value that was 30% higher than the Joukowsky pressure pulse. Pressure wave damping and phase shift significantly increased with the air pocket volume. On-going research is currently focusing on a better understanding of the observed phenomena by means of video recording of the air pocket compression and expansion during the transient event (Figure 7). An extended explanation of the air pocket behaviors for different flow regimes was presented in [6].

The potential of increasing hydropower plants flexibility through surge tanks throttling

Surge tanks in high-head power plants ensure safe and flexible transient operation of the hydraulic machinery. Orifices or throttles are often critical structural elements for the good performance of surge tanks and the stability of the whole waterway system combined with the hydraulic-mechanical equipment. The design and the dimensioning of orifices or throttles placed at surge tanks have to be carried out with great care since a non-functioning of these critical structural elements can endanger the safe operation of the whole hydropower scheme. Orifices or throttles have to produce a distinct head loss for flow entering and leaving the surge tank. In the design the best geometry has to be found which produces the wished-for head losses. The search of the most adapted geometry of the orifice or throttle is often difficult and has often to be done with hydraulic model tests in real world projects. In order to allow a fast, preliminary design of orifices, a systematic research campaign comprising laboratory experiments (Figure 8) and numerical simulations, was carried out. As part of this research a large number of different geometries of throttles, i.e. orifices,

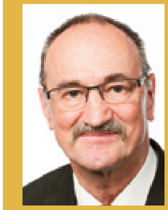


David Ferras obtained his PhD in the framework of a joint doctoral initiative between the Instituto Superior Técnico de Lisboa (IST) and the Ecole Polytechnique Fédérale de Lausanne (EPFL). During his research he focused on experimental and numerical analyses of Fluid-Structure Interaction during hydraulic transients. Currently he holds a position of lecturer/researcher at the IHE-Delft in the department of Environmental Engineering and Water Technology in the area of Water Transport and Distribution. He is also vice-chair of the IAHR-EPD committee and editor of the IAHR NewsFlash World.



Giovanni De Cesare is a senior research associate and operational Head of the hydraulic constructions platform PL-LCH of the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland. He has more than 25 years of experience in physical and numerical modelling of hydraulic structures. He specializes in various fields, such as reservoir sediment management, turbidity currents, rapid transients in pressure systems, Ultrasonic Doppler flow measurement, and river training work.

Dídia I.C. Covas is an Associate Professor at Instituto Superior Técnico (IST) and Vice President of the Civil Engineering, Architecture and Georesources Department of IST. She graduated in Civil Engineering, at IST, in 1995 and obtained a Doctoral Degree in Civil and Environmental Engineering at Imperial College, London, in 2003. She has 25 years of experience in teaching, applied and fundamental research and consultancy in various fields such as, hydraulic transients, pumping systems, energy efficiency, leak detection, water loss control, cost assessment and infrastructure asset management of water supply systems.



Anton J. Schleiss obtained a Doctorate of Technical Sciences on the topic of pressure tunnel design in 1986. He worked for 11 years for Electrowatt Engineering Ltd (now Pöyry-AFRY). In 1997, he was nominated full professor and became Director of the Laboratory of Hydraulic Constructions (LCH) of the EPFL. After retirement from teaching, he became Honorary Professor at EPFL in March 2018. He is the honorary President of the International Commission on Large Dams (ICOLD). With more than 40 years of experience he is regularly involved as a consultant and expert in large water infrastructures projects including hydropower and dams all over the world.

were tested. Based on the extensive catalogue of the orifice geometries tested and the developed empirical relationships, efficient design guidelines based on empirical formulae could be given. They were incorporated in an easy to use sheet, which allows finding efficiently the appropriate orifice geometry for a wished-for head loss. Furthermore, the systematic experiments and numerical simulations allowed also a better understanding of the hydraulic behavior of orifices in view of the influence length of the orifice, i.e. the reattachment length of the jet leaving the orifice and associated risk of cavitation [7].

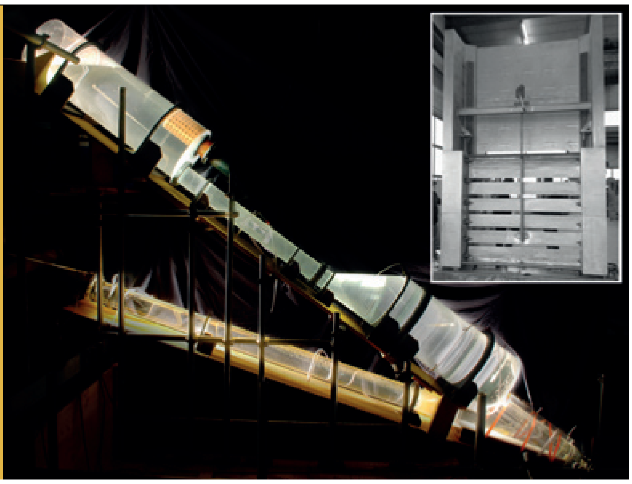


Figure 9. Gondo HPP power and flexibility increase. Physical-scale modeling (big picture) was performed to validate the design of the grid throttle (prototype under construction) placed at the bottom of the lower chamber of the existing surge tank.

The implementation of throttles in existing surge tanks of hydropower plants is an economical measure to enhance capacity and consequently flexibility in generation [8], such as the hydraulic model tests of the surge chamber and throttle for the Gondo hydropower plant (HPP), which led to an increase in power generation and flexibility of operations (Figure 9).

Can we detect, locate and quantify weak zones in pipes with the help of the water-hammer signal?

This question is especially relevant for high head pressure tunnels and shafts of hydropower plants which have to be steel-lined if rock overburden is not sufficient. Since the water can reach in an uncontrolled way the rock surface in case of failure of these water-conveying systems, high damages due to landslides and debris flow can occur. Furthermore, high strength steel is used nowadays for such steel liners, which have an increased risk of brittle and fatigue failure. Storage hydropower plants and especially pumped-storage power plants are operating today more and more under challenging conditions as they try to satisfy the highly volatile peak energy demand due to the integration in the grid of new renewable energies, like wind and solar. Therefore, an enhancement of the existing theoretical design model for steel-lined pressure shafts and tunnels as well as new monitoring approaches are necessary to manage the considerable risk in case of failure [9]. Normally the operation of hydropower plants cannot be stopped without significant generation losses and thus non-intrusive and continuous monitoring is required.

Early detection of any weak zones in pipes and steel lined tunnels is vital but also a challenge. This challenge was addressed in a research project with an experimental set-up at LCH-EPFL (Figure 10), which aimed at quantifying the influence of a local drop of wall stiffness on the pressure wave speed and wave dissipation during transients in a pipe. A complex data acquisition system was designed for this project [10]. A large number of different pipe configurations were tested. The weak reaches in the pipe were simulated by replacing the steel reaches with Aluminum and PVC materials (Figure 11). Besides pressure sensors also for the first-time geophones were used for the acquisition of water-hammer signals. The acquired data was assessed using, amongst others, the Fourier Transform, wavelet decomposition, and cross-correlation techniques [10].

The detection of a weak reach in the pipe, that is its location and drop in stiffness, is based on the following principle. When a wave (water-hammer) hits a junction, where there is a change of the hydroacoustic parameters, such as a change of section or a difference in wall stiffness, it is divided into transmitted and reflected parts (Figure 12). By comparing the outgoing wave (water-hammer) with the reflected signal, with the help of a detailed wave decomposition time analysis, the location of the weak reach and its stiffness can be back-evaluated. The measured transient pressures at the two end positions of the test pipe can be used to predict the front wave speed of an excitation traveling between them. Three different methods were applied to estimate this crucial parameter required in the time–distance transformation process: (i) the determination of the time separating the maximum front peaks of the signals, (ii) the time separating the intersection point of the regression line for the steady-state pressure and the regression line for the first pressure front, and (iii) the cross-correlation method.

The experiments showed that the wave speed and the wave dissipation ratio are good indicators of the presence of local and large changes in stiffness. When a steep front wave was generated inside the test pipe by the fast closing valve, the weak reaches represented by PVC could be located by a maximum relative mean error of about 6 % taking as reference the position to the pipe end. The local stiffness change could be quantified with a maximum relative mean error of 21% of the actual Young modulus of the pipe wall material [10]. Since the water-hammer is a complex signal, the analysis allowed only to detect important drops of stiffness (around 98% as the case for PVC). Therefore, in a further study an underwater spark generator was developed which allows to produce cavitation bubbles in the pipe resulting in very steep shock waves having a clear signal [11]. The analysis of the pressure wave reflections due to the cavitation bubble explosion, recorded by two hydrophones placed at the extremities of the test pipe, allowed identifying very precisely the wave front and correspondingly the wave speed and the weak reach location. Compared to the wave analysis from water-hammer signals, the active cavitation bubble generation in the pipe is an innovative method that significantly increased the effectiveness of the detection of wall stiffness drops.

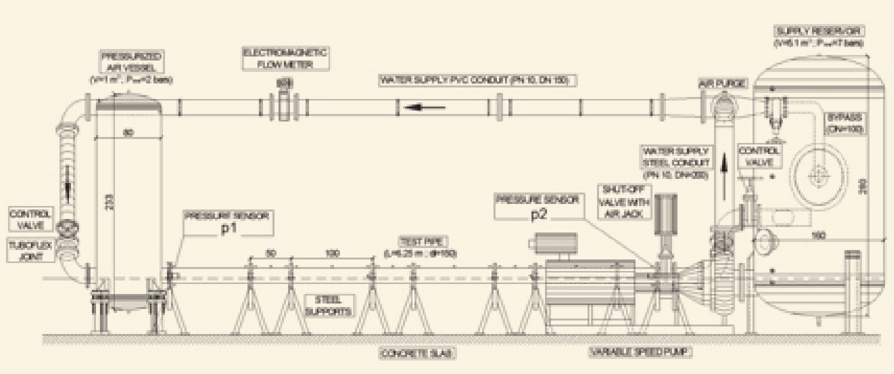


Figure 10. Experimental set-up assembled at the EPFL for the assessment of the local drop of pipe-wall stiffness dynamics.

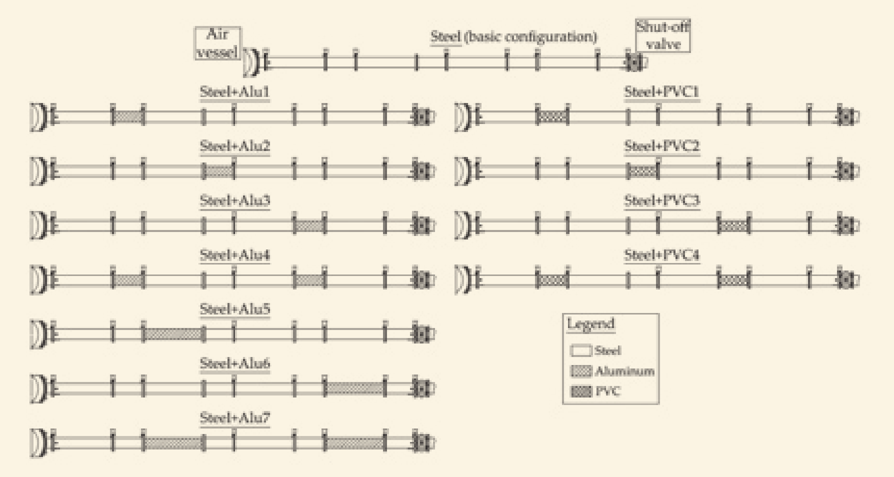


Figure 11. Tested pipe configurations. The weak reaches in the pipe are simulated by replacing the steel reaches with Aluminium and PVC materials.

In-situ measurements at the pressure shaft of the pumped-storage powerplant Grimsel II were carried out to validate the new water-hammer signal processing procedure [12]. The water-hammer signal was measured continuously at the downstream and upstream end of the pressure shaft (Figure 13). Monitoring charts were established based on the statistical quality control of the two indicators namely the water-hammer wave speed and the wave dissipation coefficient (see reference [12] for details on the monitoring charts). The wave speed was assessed from the Fourier transformation spectrums (F) while the dissipation coefficient was determined by computing the root mean square (RMS) of the signal followed by an exponential regression fitting. Three control limits representing the actual state of the steel lining in the pressure shaft were set on these charts obtained from the acquired and processed pressure data. These limits and the overall behavior of the pattern of future measured points could be used for on-line monitoring of the shaft.

Conclusions

Fluid-structure interaction affects the water-hammer signal shape, damping and timing in above-ground or non-buried pipelines, not only in hydropower systems, but also in long oil and gas pipes, cooling systems of nuclear and thermal plants, or any fluid distribution system in industrial compounds. Air entrapment has a similar effect on transient wave propagation. The collected data at LHE-IST have shown a wave shift and an increase of the wave amplitude and damping. Although undesired, the presence of air in pressurized water conduits is a frequent cause of hydraulic underperformance. Better understanding of the dynamic phenomena associated with hydraulic transients is essential for the improvement of the design and operation of hydraulic systems, and likewise for the investigation of accidents and incidents caused by water-hammer events. There is a need for both fundamental and applied research in this field and the collaborative work between LHE (IST) and PL-LCH (EPFL) represents a substantial advancement in this direction.

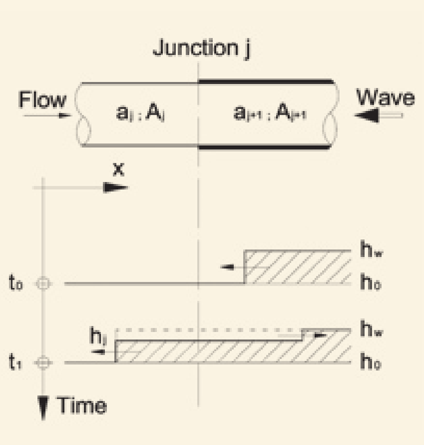


Figure 12. Schematic of a pressure wave h_W passing by a junction j representing a change in section A_j. or stiffness, which influences wave celerity a_j.

Water-hammer theory may be used for the protection, diagnosis and flaw detection of pressurized conduits. An example is provided hereby concerning throttled surge tanks, which aim at the dual purpose of anti-surge protection and flexibility in system operation.

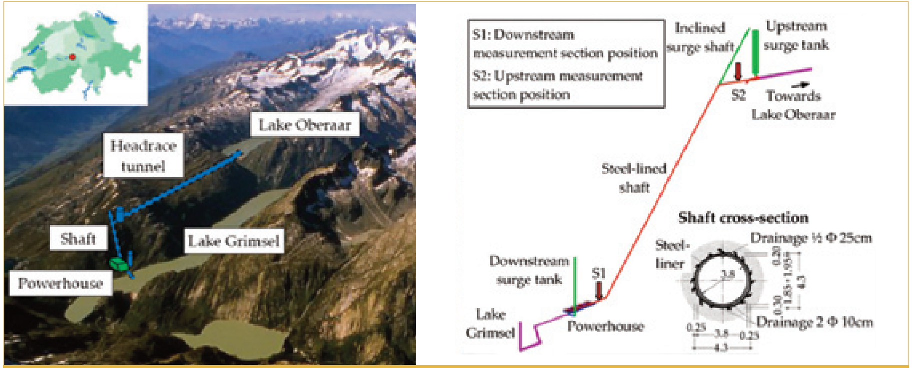


Figure 13. Grimsel II pumped-storage scheme, Left: aerial view of the site with the upper and lower reservoir, Right: schematic 3D view of the waterway system with the two positions of the data acquisition systems and a cross-section of the steel-lined shaft.

The head losses generated by throttles may reduce the water-hammer wave amplitude and increase its damping rate, safeguarding the main conduit from failure and, additionally, reducing mass oscillation phenomena. A second example of the application of water-hammer theory in hydropower conduits focuses on the detection of weak zones in steel-lined tunnels and shafts. A methodology based on the analysis of water-hammer wave transmission and reflection through pipe sections with a change of the hydroacoustic parameters is proposed. This essential principle can be applied to assess pipe defects such as leaks, bursts or obstructions. Transient based techniques for pipe flaw detection are currently an active field of research, as they require improvements in their efficiency, accuracy and robustness in order to become useful tools for standard engineering practices.

Acknowledgements

The authors acknowledge their colleagues at EPFL and IST who contributed to the research work described hereby, with special emphasis on Pedro Manso, Nuno Martins, João Ferreira, Fadi Hachem and Nicolas Adam. ■

References

[1] Ferras, David, Pedro A. Manso, Anton J. Schleiss, and Dídia IC Covas. "One-Dimensional Fluid–Structure Interaction Models in Pressurized Fluid-Filled Pipes: A Review." *Applied Sciences* 8, no. 10 (2018): 1844.

[2] Ferras, David, Pedro A. Manso, Anton J. Schleiss, and Dídia IC Covas. "Experimental distinction of damping mechanisms during hydraulic transients in pipe flow." *Journal of Fluids and Structures* 66 (2016): 424-446.

[3] Ferras, David, Pedro A. Manso, Anton J. Schleiss, and Dídia IC Covas. "Fluid-structure interaction in straight pipelines with different anchoring conditions." *Journal of Sound and Vibration* 394 (2017): 348-365.

[4] Zhou, L., Liu, D., Karney, B. and Zhang, Q. "Influence of Entrapped Air Pockets on Hydraulic Transients in Water Pipelines." *Journal of Hydraulic Engineering*, 137.12 (2011): 1686-1692.

[5] Martins, N. M. C., Delgado, J. N., Ramos, H. M. and Covas, D. I. C. "Maximum transient pressures in a rapidly filling pipeline with entrapped air using a CFD model." *Journal of Hydraulic Research*, 55.4 (2017): 506-519.

[6] Ferreira, J.P., Butarazzi, N.,Brunone, B., Meniconi, S., Covas, D.I.C. Entrapped air influence in hydraulic transients. *E-proceedings of the 38th IAHR World Congress*, September 1-6, 2019, Panama City, Panama.

[7] Adam N.J, De Cesare G., Schleiss, A. J. Influence of geometrical parameters of chamfered or rounded orifices on head losses, *Journal of Hydraulic Research*, 57.2 (2019): 263-271.

[8] Adam N.J., De Cesare G., Nicolet C., Billeter P., Angermayr A., Valluy B. and Schleiss A. J. (2018) "Design of a Throttled Surge for Refurbishment by Increase of Installed Capacity at a High-Head Power Plant". *Journal of Hydraulic Engineering*, 144.2(2017): 05017004.

[9] Hachem, F., Schleiss, A. J., "Monitoring of steel-lined pressure shafts and tunnels" *Hydropower & Dams*, 18.3 (2011): 74-77

[10] Hachem, F., Schleiss, A. J., "Effect of drop in pipe wall stiffness on water-hammer speed and attenuation" *Journal of Hydraulic Research*, 50.2 (2012): 218-227

[11] Mazzocchi, E., Pachoud, A.J., Farhat, M., Hachem, F.E., De Cesare G., Schleiss, A.J. Signal analysis of an actively generated cavitation bubble in pressurized pipes for detection of wall stiffness drops, *Journal of Fluids and Structures*, 65 (2016): 60-75

[12] Hachem, F., Schleiss, A. J., "Online monitoring of steel-lined pressure shafts by using pressure transient signals under normal operation conditions", *Journal of Hydraulic Engineering*, 138.12, (2012): 1110-1118