TRANSIENTS IN FLUIDS AND STRUCTURES

BY ARRIS S. TIJSSELING

Hydraulic transients in liquid-filled piping systems are pressure waves that travel long distances in short times. They are perfectly able to find weak spots and cause damage to pipes, supports, machinery, etc., because the wave fronts are steep, and the pressure rises (or drops) large. It is one of the most severe loadings any piping system will experience during its lifetime. A hydraulic transient causes a structural response, which may cause a smaller hydraulic transient, which causes another structural response, and so on. This is fluid-structure interaction (FSI).

Hydraulic transient analysis is essential in the design of piping systems and even more so in post-accident investigations. Computed transient pressure histories can be used as input to structural-dynamics software in order to find pipe stresses and displacements. This is usually done when the safety standards are high (nuclear industry, chemical industry, dike crossings), when the pipe layout must be light (aerospace industry), when noise must be reduced (naval submarines), when stability is an issue (hydropower stations), for buried pipes during earthquakes, naturally in hemodynamics, for fatigue life or damage prediction, and not in the least for cost reduction. The above procedure of one-way coupling gives useful additional information but maybe wrong when the pipe system has a certain degree of flexibility, mostly encountered in aboveground pipelines (Figure 1). Two-way coupling is then a more accurate approach, noting that FSI causes damping of pressure waves (because energy is transferred to the pipe walls) and has a tendency to mitigate resonance. On the other hand, in free-hanging systems, the classical Joukowsky pressure, calculated with a simple equation which is accurate only for straight uniform-section pipes without any column separation, may be exceeded by a factor of two.


Figure 1. Aboveground pipelines.


Figure 2. Shifted pipeline.


Figure 3. Broken anchor.

Hydraulic transient loads may cause pipes to move and shift on – or even fall off – their supports (Figure 2 [1]). This is an undesired situation and most frightening for personnel working nearby. The apparent solution would be to fix the pipes rigidly, but – more often than not – this leads to broken anchors (Figure 3 [2]). Some flexibility is always needed to allow for thermal expansion, but also to reduce pipe stresses in a water-hammer event. The locations and strengths of pipe supports are usually obtained from a static analysis based on conservative estimates of the fluid forces. Two-way FSI analysis may help in finding the appropriate way of dynamically supporting the piping system, noting that mass and not stiffness resists to sudden pipe motion. Fluid-structure interaction is always existent to a certain degree and many laboratory experiments on water hammer contain the (undesirable) effects of it. To avoid FSI one might embed the entire pipe in solid concrete [3] or use cubic blocks with cylindrical bores [4].

In general, (very) steep pressure wave fronts are needed to provoke structural motion and justify FSI analysis. The first coupled effect is

Figure 4. (from Joukowsky himself) Liquid flow from right to left has been arrested at position O and a pressure wave travels from left to right. The increased pressure widens the pipe and causes a dynamic hoop stress proportional to it. Pipe bending occurs only near the wave front.

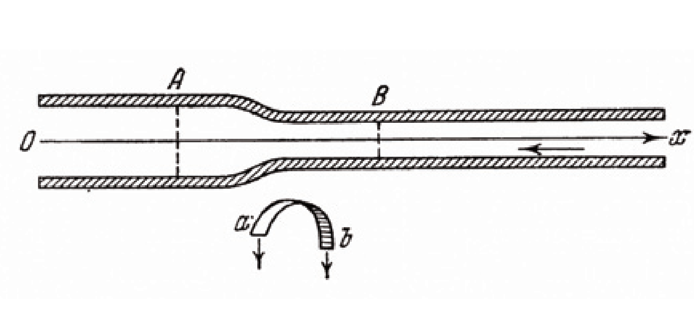
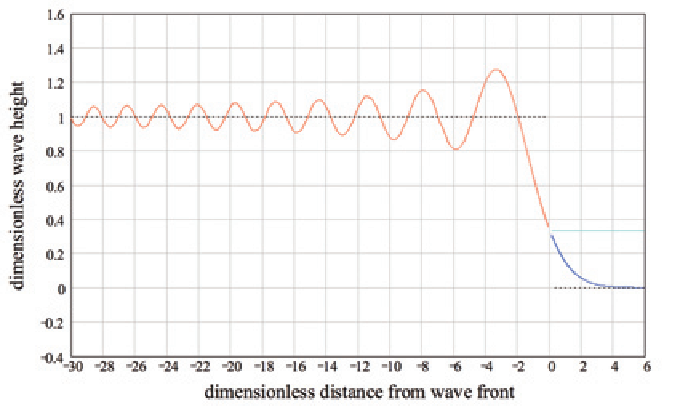


Figure 5. Skalak's theoretical wave front. Instantaneous valve closure causes a step wave front in classical water-hammer (broken line). Fluid-structure interaction disperses the wave front into a "precursor" (blue line) and trailing high-frequency oscillation (red line).



the axisymmetric bending of the pipe wall (Figure 4 [5]) which makes the traveling pressure front less steep and which induces a decaying trailing oscillation (Figure 5 [6]). This is one of the reasons that in pure liquids (without gas bubbles) wave fronts spread over lengths of tens of pipe diameters. The second coupled effect is due to unbalanced pressure forces, which make free pipe bends move; vibrating elbows are the most common generators of FSI. Pipe ovalling occurs, but as this hardly changes the cross-sectional flow area it does not affect pressure waves. The same holds for friction and damping; excluding resonance conditions, these are of less importance for the prediction of extreme pressures and stresses because of the short (acoustic) time scale: inertia and elasticity are the dominant forces such that friction will not affect the very first pressure rise in a water hammer event. It is good practice to have slow valve closures and pump stoppages, but in events of steam condensation and the collapse of column separations – somewhere in the system – almost instantaneous pressure rises are generated.

The oldest FSI formula goes back to Thomas Young [7] and relates the pipe hoop stress to the fluid pressure (linearly via the relative wall-thickness). The radial inertia of the pipe wall is ignored in this formula, which therefore is valid for frequencies well below the pipe's ring frequency. Sudden changes in hoop stress (and strain) cause axial stress waves in the pipe wall, which – due to FSI – are accompanied with changes in fluid pressure. These fast traveling (at the speed of sound in solids) pressure variations have been observed as precursors arriving ahead of the main water-hammer wave [8]. The axial waves in the pipe wall will excite bends if they are not sufficiently restrained and the resulting motion is a sort of pumping action which generates pressure waves in the liquid [9, 10]. It is noted that a traveling pressure wave does not "see" a structurally fixed bend.

To simulate FSI on a computer one needs, in addition to a water-hammer code, a structural-dynamics code, and one must couple them. Regarding the fluid, one might opt for CFD software. Regarding the structure, that is the pipes (and the supports), one may go as far as one wishes: rigid beams, elastic beams, membranes, or shells. One simplified approach is to model only the axial motion of the individual pipes in a system (which is analogue to the vibration of an elastic liquid column and might be referred to as "steel hammer"), and represent lateral and torsional motion by spring-mass-dashpot systems [10]. It has no use to simulate the entire piping system with FSI included, but one should select only those sections that can move as a consequence of unrestrained elbows, tees and U-bends.

Future challenges lie in the analysis of pipes, tubes and hoses made of a combination of different materials, like concrete and steel, and fiber-reinforced plastics. That is non-uniform and non-elastic pipes, with lining and coating, surrounded by soil and/or liquid. In fact, a blood vessel, where all hydraulic transient research started off in the 19th century, is the most striking example. The technical details of hydraulic transients with FSI and some of its history, together with the evidence of laboratory and field experiments, can be found in several review papers [11-15].

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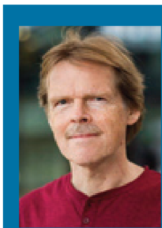
References

[1] Orynyak I, Batura A, Dubyk I (2016) Water hammer event on aboveground section of oil piping during hydro test. The ASME 2016 Pressure Vessels and Piping Division Conf., Vancouver, Canada, Paper PVP2016-63826.
[2] Hamilton M, Taylor G (1996) Pressure surge – Criteria for acceptability. The 7th Int. Conf. on Pressure Surges (Ed. A Boldy), Harrogate, U.K., pp.343-362.
[3] Holmboe EL, Rouleau WT (1967) The effect of viscous shear on transients in liquid lines. *Journal of Basic Engineering* 89:174-180.
[4] Mikota G, Manhartsgruber B, Kogler H, Hammerle F (2017) Modal testing of hydraulic pipeline systems. *Journal of Sound and Vibration* 409:256-273.
[5] Joukowsky N (1900) On the hydraulic hammer in water supply pipes. *Mémoires de l'Académie Impériale des Sciences de St.-Pétersbourg*, Series 8, 9(5):1-71 (in German).
[6] Skalak R (1956) An extension of the theory of water hammer. *Trans., American Society of Mechanical Engineers* 78:105-116.
[7] Tijsseling AS, Anderson A (2008) Thomas Young's research on fluid transients: 200 years on. The 10th Int. Conf. on Pressure Surges (Ed. S Hunt), Edinburgh, U.K., pp.21-33.
[8] Thorley ARD (1969) Pressure transients in hydraulic pipelines. *Journal of Basic Engineering* 91:453-461.
[9] Wood DJ, Chao SP (1971) Effect of pipeline junctions on water hammer surges. *Transportation Engineering Journal* 97:441-456.
[10] Wiggert DC, Otwell RS, Hatfield FJ (1985) The effect of elbow restraint on pressure transients. *Journal of Fluids Engineering* 107:402-406.
[11] Ferras D, Manso PA, Schleiss AJ, Covas DIC (2018) One-dimensional fluid-structure interaction models in pressurized fluid-filled pipes: a review. *Applied Sciences* 8(1844).
[12] Moore S (2016) A review of noise and vibration in fluid-filled pipe systems. The 2nd Australasian Acoustical Societies Conf., pp.701-710.
[13] Li SJ, Karney BW, Liu GM (2015) FSI research in pipeline systems – a review of the literature. *Journal of Fluids and Structures* 57:277-297.
[14] Wiggert DC, Tijsseling AS (2001) Fluid transients and fluid-structure interaction in flexible liquid-filled piping. *Applied Mechanics Reviews* 54:455-481.
[15] Tijsseling AS (1996) Fluid-structure interaction in liquid-filled pipe systems: a review. *Journal of Fluids and Structures* 10:109-146.



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