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WHY FLUID-STRUCTURE INTERACTION CANNOT ALWAYS BE NEGLECTED IN UNSTEADY-STATE LABORATORY TESTS; PRELIMINARY NUMERICAL AND EXPERIMENTAL ANALYSIS

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ABSTRACT

This paper highlights the importance of considering Fluid-Structure Interaction (FSI) in unsteady-state laboratory tests. Above-ground pipelines, in fact, if not perfectly constrained, can move during the generation of Water Hammer (WH). To study this, a one-dimensional mathematical model solved with the Method Of Characteristics (MOC) is used. The aim is to simulate the axial movement of a simple system tank - cast iron pipe - end valve, taking into account the combined effect of both the WH and the FSI phenomenon.

Keywords: *Water Hammer; Fluid-Structure interaction; Axial motion*

1. Introduction

Laboratory tests are a valuable tool for studying the behavior of water systems. Having a clear picture of the network functioning can greatly help the managing authorities, enhancing monitoring and maintenance operations at critical points and ensuring better protection against potential disruptions in the water supply. Laboratory environment enables us to carry out tests in a controlled and repeatable way, as well as to measure the desired physical quantities everywhere. Moreover, large laboratories—such as Water Engineering Laboratory (WEL) at the University of Perugia, which covers about 1,000 m^2—allow to host full-scale installations with pipe diameters and lengths comparable to those of real systems. However, in laboratory setups, pipelines are typically above ground, which represents a difference compared to most real-world systems where pipes are usually buried. Nevertheless, above ground pipelines are not exclusive to laboratory environments. They can also be found in real applications, such as pumping stations or various industrial facilities and buildings. In Australia, above ground transmission mains are even quite common. In these cases, insufficient constraints may allow the pipes to move during severe transients, and the FSI phenomenon cannot be neglected. FSI has been implemented in various water hammer numerical models by including appropriate equations and boundary conditions. Additional factors can also be incorporated, such as accounting for the pipe wall thickness (Tijsseling, 2007), cavitation effects (Tijsseling et al., 2005), or viscoelastic behavior (Keramat et al., 2012).
This work presents a one-dimensional mathematical model that accounts for FSI and WH by simulating the axial motion of the pipeline. Section 2 describes the experimental setup, while the laboratory tests are detailed in Section 3. Finally, the proposed numerical model is presented in Section 4.

2. Experimental setup

This work focuses on a simple system comprising a pressurized tank working at 2 bar, which supplies a cast iron pipeline with a downstream valve. The cast iron pipe, with a wave speed c = 1166 m/s, has an external diameter D_{ext} = 98 mm, an internal diameter D_{int} = 76 mm, a wall thickness e = 11 mm and a total length L = 119.54 m. A pneumatic solenoid valve (maneuver valve) is located at the downstream end of the pipe in order to perform fast closing maneuvers. A ball valve is also installed downstream of the maneuver valve and is equipped with a protractor to regulate the discharge, which is measured by an ultrasonic flowmeter. The experimental setup is anchored to the ground by means of steel strips, located every 6 meters along the pipe. The applied constraints restrict horizontal and vertical movement while allowing axial displacement of the pipe. Figure 1 shows the scheme of the experimental setup, together with some pictures of the installation at WEL. The measurement sections (pressure transducers) are located in the pressurized tank (T) and immediately upstream of the end maneuver valve (D).

Fig. 1. The experimental setup at WEL.

3. Laboratory tests

Unsteady-state tests have been carried out on the experimental setup described in Section 2 by performing fast closure maneuvers at the pneumatic end valve. Five different pre-transient discharges have been investigated, Q = 0.77 L/s, Q = 0.41 L/s, Q = 0.35 L/s, Q = 0.25 L/s and Q = 0.1 L/s. Figure 2 shows an example of pressure signals with Q = 0.1 L/s.

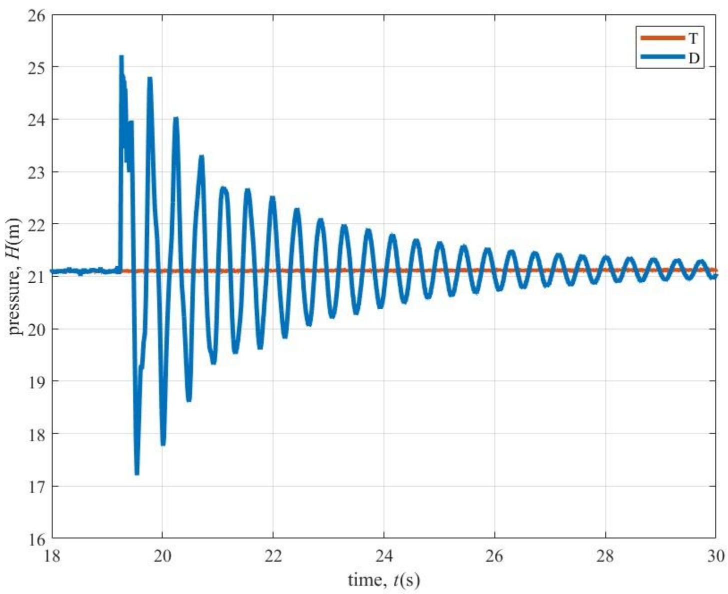

Fig. 2. Pressure signals for Q = 0.1 L/s in the tank and at the valve.

4. Mathematical model

A one-dimensional mathematical model is proposed to simulate and interpret the experimental signal (Fig. 2), by taking into account both WH and FSI. The WH is implemented by the following equations, derived with MOC (Wylie et al., 1993):

$$
\begin{cases}
\pm\frac{g}{c}\frac{dH}{dt}+\frac{dV}{dt}+\frac{f\cdot V\cdot|V|}{2\cdot Dint}=0 & (1)\\
\frac{dx}{dt}=\pm c & (2)
\end{cases}
$$

where g = acceleration of gravity [m s^{-2}], H = pressure head [m], t = time [s], V = mean flow velocity [m s^{-1}], f = friction factor, and x = axial co-ordinate [m]. Equation (1) governs the WH phenomenon and is valid along the corresponding characteristic line, represented by Eq. (2).

To reproduce the axial displacement of the cast iron pipeline, a spring-mass system is considered to be attached at the downstream end of the experimental setup, allowing it to oscillate in the axial direction. The boundary condition of the unrestrained valve for an instantaneous maneuver is thus represented by:

$$\rho\cdot g\cdot A\cdot\Delta H=m\cdot a+d\cdot v+k\cdot u \quad (3)$$

$$V=v \quad (4)$$

where ρ = water density [kg m^{-3}], A = cross sectional pipe area [m^2], ΔH = pressure-head over the valve, m = mass of the valve [kg], a = acceleration of the valve [m s^{-2}], d = damping coefficient [N s m^{-1}], v = velocity of the valve [m s^{-1}], k = stiffness of the spring mimicking the pipe [N m^{-1}] and u = axial displacement of the valve [m]. Equation (3) accounts for the oscillatory motion of the valve in the axial direction, while Eq. (4) allows for the continuity of the velocity in the absence of column separation (Tijsseling, 1993). To ensure numerical stability, Eq. (3) can be integrated using the Newmark - β = 1/4 method (Newmark, 1959), also known as the "Average acceleration method".

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