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Experimental distinction of damping mechanisms during hydraulic transients in pipe flow

David Ferràs [a,b,*], Pedro A. Manso [a], Anton J. Schleiss [a], Dídia I.C. Covas [b]

[a] Laboratory of Hydraulic Constructions (LCH), École Polytechnique Fédérale de Lausanne, Switzerland
[b] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Portugal

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ABSTRACT

The aim of the present paper is to contribute to the identification of the principal mechanical–hydraulical relationships during hydraulic transients by means of the analysis of observed transient pressure and strain waves in different pipe rigs. Four different experimental set-ups are analysed: a straight copper pipe with either moving or anchored downstream pipe-end, a coil copper pipe and a coil polyethylene pipe. Discussion highlights differences in the response of each system in terms of wave shape, damping, and dispersion. The straight copper pipe behaviour, for an anchored pipe-end, has shown the closest dynamic response to the expected one from classical waterhammer theory, being unsteady friction the most relevant damping mechanism. Fluid structure interaction dominates when the valve is released in the straight copper pipe and also has an important role in the coil copper pipe. Viscoelasticity dominates in the polyethylene pipe.

1. Introduction

The classical waterhammer theory is the result of a set of scientific achievements in a well defined framework: starting with Newton (1686) and Lagrange (1788), with studies on the acoustic wave speed in air, and Young (1808) who worked on the propagation of waves in solids; including Helmholtz and Korteweg (1878), who established waterhammer wave celerity formulae based on the criterion that hydraulic transients in pipe flow are dominated by fluid compressibility and pipe-wall distensibility; Von Kries (1883) and Joukowsky (1904) who developed the equation for the waterhammer wave amplitude; and finishing with Braun (1909, 1910) and Allievi (1902, 1913), who presented the fundamental equations which the waterhammer theory is based on.

The fundamental equations of classical waterhammer theory – mass and momentum conservation – can be derived from Navier–Stokes equations (Ghidaoui, 2004) or by directly applying the Reynolds Transport Theorem (Chaudhry, 2014) to a control volume of the pipe system. In their development several mechanisms that may significantly affect pressure waveforms are neglected, such as unsteady friction (UF), cavitation (including column separation and trapped air pockets), a number of fluid–structure interaction (FSI) effects, viscoelasticity (VE) of the pipe-wall material, leakages and blockages. Depending on the field of work, and for each application, engineers should attempt to identify and to evaluate the influence of these mechanisms in order to decide whether to include or to neglect them. Firstly, these phenomena are not commonly included in standard waterhammer software packages and when they are, they often require the specification of blind

* Corresponding author at: Laboratory of Hydraulic Constructions (LCH), École Polytechnique Fédérale de Lausanne, Switzerland.
E-mail address: david.ferras@gmail.com (D. Ferràs).

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Notation

A_f	fluid cross-sectional area (m^2)	r	inner radius of the pipe-wall (m)
a_f	pressure wave speed ($m\,s^{-1}$)	T	wave period (s)
A_s	pipe-wall cross-sectional area (m^2)	t	time (s)
a_s	axial stress wave speed ($m\,s^{-1}$)	t_v	valve closure time (s)
D	pipe inner diameter (m)	U	pipe-wall velocity ($m\,s^{-1}$)
E	pipe-wall Young's modulus (Pa)	V	fluid mean velocity ($m\,s^{-1}$)
e	pipe-wall thickness (m)	V_0	initial fluid mean velocity ($m\,s^{-1}$)
H	hydraulic head (m)	x	distance along the pipe axis (m)
H_{Jk}	Joukowsky hydraulic head (m)	ϵ_a	axial strain (–)
h	dimensionless hydraulic head (–)	ϵ_c	circumferential strain (–)
L	pipe length (m)	ν	Poisson's ratio (–)
m_v	valve mass (kg)	ρ_f	fluid density ($kg\,m^{-3}$)
p	fluid pressure (Pa)	ρ_s	pipe-wall density ($kg\,m^{-3}$)
R	coil radius (m)	σ_a	pipe-wall axial stress (Pa)
		σ_c	pipe-wall circumferential stress (Pa)
		τ	valve closure degree (–)

parameters which the user is not sensitive to. Secondly, these effects tend to be often 'hidden' in real systems being, therefore, forgotten (Bergant et al., 2008a,b). Consequently, the expertise of the modeller becomes crucial when add-ons are to be included into the classical waterhammer model.

The referred mechanisms have been largely studied by focusing on single phenomena. Though, several examples can be found in the literature combining different mechanisms either in experimental or numerical analyses, such as experiments in plastic and metallic pipes (Krause et al., 1977; Williams, 1977); development of numerical models incorporating both FSI and VE (Weijde, 1985; Walker and Phillips, 1977; Stuckenbruck and Wiggert, 1986); analysis of FSI and cavitation (Tijsseling, 1993, 1996; Tijsseling et al., 1996); analysis of VE in combination with UF (Covas et al., 2004a); analysis of longitudinal stiffness heterogeneity by means of the combination of aluminium and PVC pipe reaches in an experimental set-up (Hachem and Schleiss, 2012); and analysis of FSI, column separation and UF in a viscoelastic pipe (Keramat et al., 2012).

The purpose of the present research is to give experimental insight in the distinction and identification of the three phenomena that frequently affect the transient pressure wave, namely fluid–structure interaction, pipe-wall viscoelasticity and unsteady friction. These phenomena lead to increased damping and dispersion of the pressure transient wave. The aim is to highlight the features, from an empirical standpoint, in which way each mechanism affects the wave attenuation, shape and timing.

Experimental tests were carried out in three pipe rigs. The three experimental facilities, assembled at the Laboratory of Hydraulics and Environment of Instituto Superior Técnico (LHE/IST), Lisbon, Portugal, consist of (i) a straight copper pipe, which is tested for different supporting set-ups; (ii) a coil copper pipe, whose response in transient conditions is strongly affected by the coil geometry; and (iii) a coil polyethylene pipe, clearly showing the dominant effect of the pipe-wall viscoelasticity.

The key innovative features of this paper are (i) the comparison of different pressure traces collected in pipe-rigs with different supporting conditions (moving or anchored pipe end), geometrical configurations (straight and coiled) and pipe materials (metal and plastic), under similar initial conditions, complemented with (ii) the physically based discussion, supported by bibliographic references, of different phenomena affecting and dominating waterhammer in each case. Finally, (iii) transient pressure measurements are complemented with axial and circumferential strain measurements to better understand the phenomena and to support conclusions.

The experimental evidence presented herein is being used to develop, calibrate and validate numerical models to simulate hydraulic transients in the time-domain, including fluid–structure interaction, pipe-wall viscoelasticity and unsteady friction, objects of other communications and research papers. The value and novelty of the actual research focus lies on the benefits of an integral assessment of the empirical distinction between different damping mechanisms affecting waterhammer tests carried out in varied experimental facilities.

2. Experimental data collection

2.1. Straight copper pipe

A straight copper pipe (SCP) rig was assembled at LHE/IST. The system is composed of a 15.49 m pipe, with an inner diameter $D = 0.020$ m and pipe-wall thickness $e = 0.0010$ m. Young's modulus of elasticity and Poisson ratio of the copper material were experimentally determined by measuring stress–strain states over a pipe sample for the experimental range of pressures. The obtained experimental values were Young's modulus of elasticity $E = 105$ GPa and the Poisson ratio