Journal of Fluids and Structures 28 (2012) 434–455

Contents lists available at SciVerse ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Fluid–structure interaction with pipe-wall viscoelasticity during water hammer

A. Keramat [a,b,*,1], A.S. Tijsseling [b,2], Q. Hou [b], A. Ahmadi [c,3]

[a] Department of Civil Engineering, Shahrood University of Technology, Iran
[b] Department of Mathematics and Computer Science, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[c] Department of Civil Engineering, Shahrood University of Technology, Post Code: 3619995161, Shahrood, Iran

ARTICLE INFO

Article history:
Received 1 March 2011
Accepted 2 November 2011
Available online 6 December 2011

Keywords:
Water hammer
Fluid transient
Pressure surge
Fluid–structure interaction
Pipe vibration
Plastic pipe
Viscoelasticity

ABSTRACT

Fluid–structure interaction (FSI) due to water hammer in a pipeline which has viscoelastic wall behaviour is studied. Appropriate governing equations are derived and numerically solved. In the numerical implementation of the hydraulic and structural equations, viscoelasticity is incorporated using the Kelvin–Voigt mechanical model. The equations are solved by two different approaches, namely the Method of Characteristics–Finite Element Method (MOC-FEM) and full MOC. In both approaches two important effects of FSI in fluid-filled pipes, namely Poisson and junction coupling, are taken into account. The study proposes a more comprehensive model for studying fluid transients in pipelines as compared to previous works, which take into account either FSI or viscoelasticity. To verify the proposed mathematical model and its numerical solutions, the following problems are investigated: axial vibration of a viscoelastic bar subjected to a step uniaxial loading, FSI in an elastic pipe, and hydraulic transients in a pressurised polyethylene pipe without FSI. The results of each case are checked with available exact and experimental results. Then, to study the simultaneous effects of FSI and viscoelasticity, which is the new element of the present research, one problem is solved by the two different numerical approaches. Both numerical methods give the same results, thus confirming the correctness of the solutions.

1. Introduction

There are four important items, which may affect classical water-hammer results: unsteady friction (UF), column separation (CS), fluid–structure interaction (FSI) and viscoelasticity (VE), each of which has been separately investigated and verified in various researches. With the inclusion of two or more of these items in the analysis, eleven possibilities are offered from which some combinations already have been studied and some have not. The combinations of VE and UF (Covas et al., 2004a,b, 2005; Duan et al., 2010; Soares et al., 2008), CS and UF (Bergant et al., 2008a,b; Bughazem and Anderson, 2000), FSI and UF (Elansary et al., 1994), FSI and CS (Fan and Tijsseling, 1992; Tijsseling and Vardy, 2005; Tijsseling et al., 1996) and VE and CS (Hadj-Taïeb and Hadj-Taïeb, 2009; Keramat et al., 2010; Soares et al., 2009) have

---

[*] Corresponding author at: Department of Civil Engineering, Shahrood University of Technology, Iran. Tel.: +989161117850.
E-mail addresses: alireza.keramat@gmail.com (A. Keramat), a.s.tijsseling@tue.nl (A.S. Tijsseling), q.hou@tue.nl (Q. Hou), a.ahmadi@shahroodut.ac.ir (A. Ahmadi).

[1] Visiting scholar at the Department of Mathematics and Computer Science, Eindhoven University of Technology.

[2] Tel.: +31 40 247 2755; fax: +31 40 244 2489.

[3] Tel./fax: +98 273 3300 259.

0889-9746/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jfluidstructs.2011.11.001

Nomenclature

Scalars

A	cross-sectional area (m^2)
B	constants
c	wave speed (m/s)
D	inner diameter of pipe (m)
E	modulus of elasticity (Pa); spring “stiffness” in Kelvin–Voigt model (Pa)
e	pipe wall thickness (m)
F	force (N)
g	gravitational acceleration (m/s^2)
H	piezometric head (m)
I	convolution integral
J	creep compliance function of pipe wall material (Pa^{-1})
K	fluid bulk modulus (Pa)
L	pipe length (m); Laplace operator
l	element length, mesh spacing (m)
p, q	parameters in stress–strain relation
Q	discharge (m^3/s)
u	displacement (m)
V	cross-sectional averaged fluid velocity (m/s)
α_r	averaging factor for radial stress
α_v	opening ratio of valve
β	Newmark parameter
γ	constant
Δt	numerical time step, mesh spacing (s)
ε	strain $\partial u/\partial z$
θ	angle between the pipe axis and horizontal surface (rad)
λ	eigenvalue (m/s)
μ	viscosity of dashpot (kg/(m s))
ρ	mass density (kg/m^3)
σ	stress (Pa)
τ	retardation time (s)
υ	Poisson’s ratio

Matrices and vectors

$\mathbf{A}$, $\mathbf{B}$	coefficient matrices of the four FSI equations
$\mathbf{f}$	element force vector (up to a constant factor)
$\mathbf{K}$ ($\mathbf{M}$)	stiffness (mass) matrix of each element (up to a constant factor)
$\mathbf{r}$	right-hand-side vector of the four FSI equations
$\mathbf{S}$, $\mathbf{T}$, $\mathbf{\Lambda}$	matrices used in the diagonalization of the four FSI equations
$\mathbf{s}$	vector of shape functions
$\mathbf{u}$	vector of axial displacements of each element

Subscripts and superscripts

0	steady state; leading spring in Kelvin–Voigt model
$\dot{}$ ($\ddot{}$)	first (second) derivative with respect to time
$'$	quasi-steady friction coefficient in Soares et al. (2008)
$''$	unsteady friction coefficient in Soares et al. (2008)
$'''$	viscoelasticity coefficient
$''''$	Poisson coupling coefficient
$\bar{}$	Laplace transformed variable
A_1, A_2, A_3, A_4	computational sections at previous time
D	dashpot
f	fluid
KV	Kelvin–Voigt
k	number of each Kelvin–Voigt element
n	negative characteristic line
P	unknown computational variable
p	positive characteristic line
r	radial direction
S	spring
t	pipe, tube
v	valve
z	axial direction of pipe
ϕ	circumferential direction of pipe

already been investigated. The remaining combination of two, namely FSI and VE, is the scope of this article. Combinations of three were modelled by Neuhaus and Dudlik (2006) (CS, UF and FSI) and Warda and Elashry (2010) (CS, UF and VE).

Fluid–structure interaction deals herein with the transfer of momentum and forces between a pipeline and its contained fluid. This matter has been investigated widely for elastic pipes and various experimental and numerical researches have been reported (Tijsseling, 1996; Wiggert and Tijsseling, 2001). In the numerical researches (most of which are in the time domain as opposed to the frequency domain), solutions based on the Method of Characteristics (MOC), the Finite Element Method (FEM), or a combination of these, are predominant. Lavooij and Tijsseling (1991) presented two different procedures for computing FSI effects: full MOC uses MOC for both hydraulic and structural equations and in MOC–FEM the hydraulic equations are solved by the MOC and the structural equations by the FEM. Using the MOC–FEM approach, Ahmadi and Keramat (2010) investigated various types of junction coupling. Heinsbroek (1997) compared MOC and FEM for solving the structural beam equations for the pipes and his conclusion for axial vibration was that both full MOC and MOC–FEM are valid methods that give equivalent results. In the current research, these two approaches were selected and developed for transients in pipes with viscoelastic walls.

For pipes made of plastic such as polyethylene (PE), polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS), viscoelasticity is a crucial mechanical property that changes the hydraulic and structural transient responses. Covas et al. (2004a, 2005) presented a model that deals with the dynamic effects of pipe-wall viscoelasticity for hydraulic transients. The model included an additional term in the continuity equation to describe the retarded radial wall deformation based on a creep function fitted to experimental data. The governing equations were solved using MOC and it was said that, unlike the classical water-hammer model, only a model that includes viscoelasticity can predict accurately transient pressures. A more detailed research in this field by Soares et al. (2008) gave a general algorithm to include viscoelasticity and unsteady friction within the conventional MOC solution procedure. Their final conclusion that unsteady friction effects are negligible when compared to