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Fluid–structure interaction with viscoelastic supports during waterhammer in a pipeline

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ABSTRACT

Waterhammer modeling with fluid–structure interaction (FSI) in a pipeline with axial viscoelastic supports is the aim of this research. The viscoelastic materials of supports (or the pipe wall) were described using the generalized Kelvin–Voigt model. Hydraulic governing equations were solved by the method of characteristic (MOC) and axial vibration equation of the pipe wall was solved using the finite element method (FEM) in the time domain. For a typical case study, four different types for supporting the pipeline in the axial direction: fully free to move; fixed (rigid support); elastic and viscoelastic supports, subject to a waterhammer are analyzed and the results are scrutinized. The results quantitatively confirm that the use of supports with viscoelastic behavior in the axial direction of the pipeline can significantly reduce axial-pipe vibrations (displacements and stresses). The consequences of this structural damping on the attenuation of the internal fluid pressure are further demonstrated.

1. Introduction

Structural damping, the manifestation of energy dissipating property of materials, is an important intrinsic mechanism observed in structural vibration because it causes reduction in the dynamic and acoustic responses. Viscoelastic materials bring about much damping as their long molecular chains are deformed by internal forces, thus causing a large amount of energy absorption. The use of pipes made from such polymeric materials is therefore an advantage in the control of vibrations.

Several waterhammer models for viscoelastic pipes have been reported in the literature (Güney, 1983; Kokoshvili, 1970; Covas et al. 2004a, b, 2005; Brunone et al., 2000; Brunone and Berni, 2010), from which they ignore pressure wave interactions with stress waves propagated in the pipe wall. More complete waterhammer models take fluid–structure interaction into account in elastic or viscoelastic pipes. The investigation of wave fronts degradation due to FSI and viscoelasticity was carried out by Bahrar et al. (1998). Rachid and Stuckenbruck (1989) presented a model for FSI transients in plastic pipes and found that the high frequencies caused by FSI virtually vanished as a result of viscoelasticity by the end of the first waterhammer cycle. Plastic circumferential (hoop) deformations were included in the simulations to consider FSI (Rachid and Costa Mattos,1998a), elasto-plastic (Rachid and Costa Mattos, 1995, 1998b) or elasto-viscoplastic (Rachid et al., 1994) material properties of pipes to estimate their damage accumulation and structural failure.

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Nomenclature

Scalars

A	cross-sectional area (m^2)
B, C	constants
c	wave speed (m/s)
D	inner diameter of the pipe (m)
d	distance between axial supports
E	modulus of elasticity (Pa)
e	pipe wall thickness (m)
F	force (N)
G	stress relaxation function of viscoelastic material (Pa)
g	gravitational acceleration (m/s^2)
H	piezometric head (m)
I	convolution integral
J	creep compliance function of viscoelastic material (Pa^{-1})
K	fluid bulk modulus (Pa)
L	length (m)
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_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)
μ	viscosity of dashpot (kg/(m s))
ρ	mass density (kg/m^3)
σ	stress (Pa)
τ	retardation time (s)
$\hat{\tau}$	stress relaxation time (s)
υ	Poisson's ratio

Matrices and vectors

$\mathbf{f}$	element force vector (up to a constant factor)
$\mathbf{B}$	spatial derivative of shape function
$\mathbf{K}(\mathbf{M})$	stiffness (mass) matrix of each element (up to a constant factor)
$\mathbf{N}$	vector of shape functions
$\mathbf{S}$	spatial derivative operator
$\mathbf{u}$	vector of axial displacements of each element
$\mathbf{W}$	weight function

Subscripts and superscripts

0	steady state; leading spring in Kelvin–Voigt model
$\dot{}\ (\ddot{})$	first (second) derivative with respect to time
$'''$	rheological behavior coefficient of pipe wall
$''''$	Poisson coupling coefficient
A_1, A_2	computational sections at previous time
f	fluid
KV	Kelvin–Voigt
k	number of each Kelvin–Voigt element
ms	middle support
n	negative characteristic line
P	unknown computational variable
p	positive characteristic line
R	rod
r	radial direction
s	support
t	pipe, tube
v	valve
z	axial direction of pipe
ϕ	circumferential direction of pipe

Viscoelasticity and FSI were modeled by Hachem and Schleiss (2011) to determine wave speeds in steel-lined rock-bored tunnels. Achouyab and Bahrar (2011) published a numerical study on water hammer with FSI and viscoelasticity using the MOC–FEM approach to solve the equations. Two years later, they presented an MOC approach to solve equations of waterhammer problems with FSI and viscoelasticity (Achouyab and Bahrar, 2013). In the research by Keramat et al. (2010, 2012), presented mathematical model for FSI with viscoelasticity was solved by two methods: full MOC and MOC–FEM. Keramat and Tijsseling (2012) investigated the combination of column separation, unsteady friction and fluid–structure interaction in a viscoelasticity pipe. Tijsseling and Vardy (1996) investigated the use of suppression devices on reducing water hammer and pipe vibration. It was demonstrated that a short plastic extension significantly influenced the axial vibration of a water-filled steel pipe. With longer plastic sections a significant reduction in the amplitude of vibration was predicted. In another experiment on the damping of water hammer due to viscoelastic effects, Tijsseling et al. (1999) investigated water hammer in a steel pipeline fitted with an internal air-filled plastic tube of rectangular cross-section. However, it is not always possible to use such vibration damping materials as the main ingredient of the whole pipelines. An alternative approach to control oscillations is the use of supports with viscoelastic behavior that can attenuate vibrations when transmitting forces to earth.

Kang and Kim (1996) investigated the effects of supports with complex stiffness on the vibration of beams and plates, in which the variation of modal properties with support stiffness was calculated. Effects of viscoelastic supports on reducing vibration and noise of structures subject to excitations have been studied in several researches about structural engineering. Fan and Kim (1997) investigated the effects of VE boundary supports on transient sound radiated from a rectangular plate. It was shown that viscoelastic treatment at the boundary support is an effective practical tool for reduction of vibrations. In addition, the size of the viscoelastic support should be adjusted to maximize the treatment efficiency. Similar results were

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