Journal of Fluids and Structures 26 (2010) 1123–1141

JOURNAL OF FLUIDS AND STRUCTURES

www.elsevier.com/locate/jfs

Investigation of fluid–structure interaction with various types of junction coupling

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Received 16 July 2008; accepted 21 August 2010
Available online 20 October 2010

Abstract

In this study of water hammer with fluid–structure interaction (FSI) the main aim was the investigation of junction coupling effects. Junction coupling effects were studied in various types of discrete points, such as pumps, valves and branches. The emphasis was placed on an unrestrained pump and branch in the system, and the associated relations were derived for modelling them. Proposed relations were considered as boundary conditions for the numerical modelling which was implemented using the finite element method for the structural equations and the method of characteristics for the hydraulic equations. The results can be used by engineers in finding where junction coupling is significant.

Keywords: Fluid–structure interaction; Piping systems; Water hammer; Junction coupling

1. Introduction

Transient flow occurs due to a disturbance in the steady flow, such as valve closing or pump shut-down. It can affect the structural piping system due to interaction between the structure and the contained liquid. In the study of fluid–structure interaction (FSI) in piping systems, the most significant mechanism is junction coupling, as compared with the other coupling mechanisms, namely Poisson and friction coupling (Wiggert and Tijsseling, 2001) in the more flexible piping systems (Heinsbroek and Tijsseling, 1994; Heinsbroek, 1997). Junction coupling takes place at unsupported discrete points of the piping systems such as unrestrained valves, branches, closed ends, pumps, etc. The main concept can be numerically implemented by using appropriate boundary conditions which will mutually relate structural and hydraulic values to each other.

FSI in piping systems, considering the effects of column separation, has already been investigated in by Tijsseling (1993). In that study, the method of characteristics (MOC) has been used for numerical modelling of both structural and hydraulic equations. Fan and Tijsseling (1992) have made a study of the simultaneous occurrence of cavitation and FSI. In this research, numerical simulation and experiment concerned a single pipe, while in Tijsseling et al. (1996), a

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doi:10.1016/j.jfluidstructs.2010.08.002

Nomenclature

A_p (A_f)	cross-sectional area of pipe wall (flow) (m^2)
a	pressure wave speed (m/s)
D	inner diameter of pipe (m)
E	Young's modulus of pipe wall material (Pa)
e	pipe wall thickness (m)
f	Darcy–Weisbach friction coefficient
G	shear modulus of pipe wall material (Pa)
g	gravitational acceleration (m/s^2)
H	piezometric head (m)
I	second moment of cross-sectional inertia (m^4)
I_{pump}	inertia of the pump impeller (kg m^2)
N	rotational speed of pump (rpm)
N_R, T_R, H_R, Q_R	rated quantities of rotational speed, shaft torque, head and discharge
P	fluid pressure (Pa)
Q	discharge (m^3/s)
T	shaft torque of the pump (N m)
V	cross-sectional averaged fluid velocity (m/s)
X, Y, Z	directions of global coordinate system
x	axial direction (x-direction of local coordinate system)
y, z	lateral directions (y-, z-direction of local coordinate system)
α	dimensionless rotational speed
β	dimensionless shaft torque of the pump
γ	weight density of fluid (N/m^3)
Δt	numerical time step, mesh spacing (s)
Δx	element length, mesh spacing (m)
$\eta(w)$	lateral displacement in xz (xy) plane (m)
θ	axial rotation of element (rad)
ν	Poisson's ratio
ξ	axial displacement (m)
ρ	fluid mass density (kg/m^3)
τ	temporary opening ratio of valve
υ	dimensionless discharge of pump
$\forall$	cavity volume (m^3)

Matrices and vectors

$\mathbf{C}$	structural damping matrix (kg/s)
$\mathbf{D}$	displacement vector of nodes (m)
$\mathbf{d}^{(e)}$	displacement vector of element (m)
$\mathbf{F}$	load vector in global coordinat system (N)
$\mathbf{f}^{(e)}$	force vector of element (N)
$\mathbf{K}^{(e)}$	stiffness element matrix (N/m)
$\mathbf{M}$	system mass matrix (kg)
$\mathbf{R}^{(e)}$	transformation matrix of element
$\mathbf{S}$	system stiffness matrix (N/m)

Subscripts and superscripts

$\dot{(\,)}$ ($\ddot{(\,)}$)	first (second) derivative with respect to time
(e)	element properties
f	fluid
glo	global coordinate system
i	spatial discretization index
loc	local coordinate system
n	time discretization index
p	pipe, pump
R	rated quantities (value of its holder is at the point of best efficiency)
val	valve
x, y, z	directions associated with local coordinate system

second pipe was added forming a one-elbow system. The other significant work combining FSI and cavitation by Vardy et al. (1996) concerns a T-piece pipe.

Lavooij and Tijsseling (1991) presented two different procedures for modelling the FSI effects: MOC which is used for both hydraulic and structural governing equations against MOC–FEM where the hydraulic equations are solved by the method of characteristics and the structural equations are solved by the finite element method in combination with a direct time integration scheme. Cases including bends and valves with gradual closure were studied. Furthermore, Heinsbroek (1997) compared two different ways including MOC and FEM for solving the structural equations. The contribution of this work was the comparison of Euler–Bernoulli and Timoshenko beam theories when used in the mentioned ways of solution. This study showed that FSI in pipeline systems can adequately be investigated by application of MOC and FEM for hydraulics and structure of a piping system, respectively. The preceding solution was employed to study the coupling mechanisms in branched piping systems (Keramat, 2006). Jazayeri (2004) gave solutions for hydraulic equations using MOC and structural equations using the control volume method.

In addition to the time-domain analysis such as the present work, many researchers have studied the theoretical and experimental aspects in the frequency domain (Jong, 1994; Zhang et al., 1999). Li et al. (2003) and Tijsseling (2003) have independently solved the main axial FSI equations analytically. In both these studies analytical junction and Poisson coupling modelling has been considered.

An analysis of a two-elbow pipe system done by Moussou et al. (2000) studies perspicuously the effects of junction coupling. Generally, there are many other experimental and numerical researches which have been carried out for