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Identification of the strength of junction coupling effects in water hammer

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A B S T R A C T

In order to analyse the effects of junction coupling during water hammer in piping systems, a test facility has been designed and constructed. The main objective is to identify the dependence on the bend geometry and the strength of two-way coupling, and to derive a critical, geometric parameter, by means of which it is easily evaluated whether significant two-way effects occur or not. Oscillation experiments on movable U-shaped bends with various geometries were carried out. The excitation was realised by water hammer. The bend configurations differed in distance between the parallel levers, which results in different excitation forces, masses and stiffnesses. Inter alia the vertical displacement of the bend and the pressure inside the pipe were measured for various free oscillating lengths while the rest of the piping system was restrained. The results are displayed in curves of the maximum displacement and frequency spectra of the pressure and the displacement for the different bend configurations. Additional experiments with variable excitation at the coincidence frequency for two bend configurations were performed. Only for the medium and long bend configurations, two-way junction coupling effects were resolved. The strength of the coupling was found to be independent of the excitation, which just scaled the amplitudes. A quantification of the strength of the two-way coupling effects was performed by an analogy with the two-mass oscillator. This method was verified using coupled simulations. Owing to the good agreement between the results of the experiments and the simulations, additional bend configurations were calculated. Using this data, it is possible to evaluate the strength of the coupling on the basis of the geometry and mass of the bend.

1. Introduction

Water hammer is a transient fluid mechanical event. It is most important for piping systems which convey liquids because of the high density of these fluids. Water hammer analysis represents a fundamental part within the design process of piping systems for power plants, procedural facilities or water distribution networks. It has to be ensured that certain events in which water hammer can be produced do not damage the piping system. These events include sudden valve closure or opening and pump start-up or shutdown (Wylie and Streeter, 1985). Velocity changes of the fluid ΔU cause pressure changes Δp. The relationship is given by Eq. (1) and is known as the Joukowsky formula (Joukowsky, 1898), where ρ_f denotes the density of the fluid and c_f the speed of sound of the fluid.

$$\Delta p = \rho_f c_f \Delta U \quad (1)$$

Mostly, water hammer analysis does not consider two-way fluid–structure interaction (FSI) due to high numerical costs.

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Nomenclature

c_1, c_2	spring stiffness
c_r	stiffness ratio
c_f	speed of sound of fluid
$c_{f,0}$	free speed of sound of fluid
c_p	precursor wave velocity
D_i	inner diameter
D_o	outer diameter
DN	nominal diameter
E	Young's modulus
f	frequency
f_c	coupled frequency
f_f	fluid frequency
f_{max}	frequency at local maximum
f_s	structural frequency
Δf	change in frequency
F	force
F_e	excitation force
FSO	full scale output
i	imaginary unit
K	bulk modulus
$l_\perp$	vertical length
L	length of the piping system
L_v	variable length
m	mass
m^*	lever-weighted mass
m_f	fluid mass
m_p	point mass
m_r	mass ratio
$m_{r,c}$	corrected mass ratio
max	maximum
min	minimum
omv	of measured value
p	pressure
Δp	pressure change
PN	nominal pressure
Q	discharge
$R_{90°}$	radius of 90°-bend
s	pipe wall thickness
SDOF	single-degree-of-freedom
t	time
T_w	water temperature
U	flow velocity
U_{mean}	mean flow velocity
ΔU	velocity change
x, y, z	coordinates
y	support position
y_{mc}	coordinate of the centre of mass
β_1, β_2	mode shapes
ϵ	strain
φ	rotation angle
ρ_f	density of the fluid
ν_P	Poisson's ratio
ξ	displacement
$\dot{\xi}$	velocity
$\ddot{\xi}$	acceleration
ξ^*	scaled displacement
$\tilde{\xi}$	displacement amplitude
ξ_0	initial displacement
ω	angular frequency
ω_1, ω_2	natural angular frequencies
ω_0, $\omega_{1,0}$, $\omega_{2,0}$	natural frequencies of SDOF system
$\Delta\omega^*$	accumulated relative change in frequency

Generally, FSI during water hammer in piping systems comprises three different coupling types. Poisson coupling is related to the radial and axial movement of the pipe wall and causes a reduction of the speed of sound in the fluid. The structural propagation velocities are also affected. Korteweg (1878) was one of the first to explain this effect.

It is often integrated in the calculation of the fluid system by considering the variation of the propagation velocity. Korteweg's original formula is given by Eq. (2) (Korteweg, 1878), in which $c_{f,0}$ denotes the speed of sound of the free fluid, D_i is the inner pipe diameter, s represents the pipe wall thickness and E is Young's modulus of the pipe wall material:

$$c_f = c_{f,0}\left(1 + \frac{D_i \rho_f c_{f,0}^2}{sE}\right)^{-1/2}. \tag{2}$$

A further impact of Poisson coupling is the generation of an axial stress wave because of the lateral contraction of the pipe. This wave travels with a velocity which is higher than the propagation velocity of water hammer and lower than the speed of sound of the pipe wall material. The propagation velocity of the wave is indicated with c_p in Fig. 1(a). The contraction of the pipe again creates a small rise in the pressure inside the pipe (Hansson and Sandberg, 2001). In the literature, these waves are called precursor waves (Williams, 1977; Thorley, 1969; Li et al., 2003; Sharp and Sharp, 1996). Friction coupling is a result of the wall shear stresses. There are pressure losses inside the fluid and the equivalent forces act on the pipe wall. The last coupling type, junction coupling, occurs at movable bends or tees etc. (Wiggert and Tijsseling, 2001; Tijsseling, 1996). The effects of this coupling type are most significant (Heinsbroek, 1997; Ahmadi and Keramat, 2010). Due to the movement of the pipe, secondary pressure waves are generated (Fig. 1(b)). Whereas Poisson and friction coupling take effect all over the piping system, junction coupling acts at specific locations such as bends, tees or diameter steps.

In the analysis of pipe oscillations, the standard approach considers one-way FSI. A two-way FSI calculation is an optional procedure to obtain more accurate results (VDI, 2004). In the case of one-way FSI, there is no reaction from the fluid to the calculated displacements of the structure. If the piping system is rigidly anchored, the method is justified (Lavooij and Tijsseling, 1991). If not, the introduction of FSI may show an effect. As a consequence, there can be changes in the amplitudes and the frequencies (Heinsbroek and Tijsseling, 1994). On the hydraulic side, FSI can cause higher and lower extreme pressures and a frequency reduction as well as a frequency rise (Wiggert and Tijsseling, 2001; Tijsseling, 1996; Kuiken, 1988; Heinsbroek, 1993;