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Measurements of junction coupling during water hammer in piping systems

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ABSTRACT

For the analysis of the effects of fluid–structure interaction (FSI) during water hammer in piping systems, a test facility has been designed and constructed. The research objective is to show on the basis of two specific examples that the necessity of considering FSI is strongly dependent on the boundary conditions of the system. Resonance experiments on movable bends in two piping system configurations focused on junction coupling were carried out. These configurations differ in the length of the hydraulic system and in the geometry of the oscillating bend. The displacement of the bend and the pressure inside the pipe were measured for various free oscillating lengths of the bend while the rest of the piping system was restrained. The results are displayed in resonance curves and frequency spectra for the different configurations. In both cases a correlation between the pressure and the displacement spectrum shows a transfer of momentum from the fluid to the structure, but only in the configuration with the long oscillating pipe section can a reaction of the fluid on the motion of the structure be identified. Frequency shifts of the pressure and a splitting of the pressure peak were observed. The time signals confirm that the effects of FSI are most significant in one system configuration which is strongly influenced by the bend geometry. Furthermore a parameter is presented which quantifies the effects of junction coupling based on the geometrical and hydraulic properties of the bend and the system.

1. Introduction

Water hammer analysis is a fundamental part of the design process of piping systems for power plants or water distribution networks. In most cases, these calculations do not include fluid–structure interaction (FSI). In this paper, FSI represents a two-way interaction in contrast to a one-way interaction where a load is only transmitted from the fluid to the structure.

FSI comprises three different coupling types. Poisson coupling is related to the radial 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 in Eq. (1) (Korteweg, 1878), in which c_0 denotes

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Nomenclature

A	area
c	water hammer propagation velocity
c_0	speed of sound
c_p	propagation velocity of the precursor wave
d_i	inner diameter
d_o	outer diameter
DN	nominal diameter
E	Young's modulus of the pipe wall material
f_f	fluid frequency
f_s	structural frequency
FSO	full scale output
g	acceleration of free fall
H	pressure head
l	length of the piping system
m^*	mass ratio
m'	lever weighted mass
n	mode number
$\mathbb{N}$	natural numbers
p	pressure
p_{max}	maximum allowable pressure
PN	nominal pressure
Q	discharge
R	radius
s	pipe wall thickness
x	displacement
x_{max}	mean maximum displacement
y	support position
α	rotation angle of the flap
ε	hydraulic proportion factor
η	quantification parameter
ρ_f	density of the fluid

the free speed of sound of the fluid, ρ_f is the density of the fluid and E is the Young's modulus of the pipe wall material:

$$c = c_0\left(1+\frac{d_i\rho_f c_0^2}{sE}\right)^{-1/2}. \tag{1}$$

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. 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. 2). 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 (Verein Deutscher Ingenieure, 2004). In the case of one-way FSI, there is no reaction from the fluid on 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; Erath, 1998; Wood, 1969; Wood and Chao, 1971; Enkel and Grams, 1997; Wiggert et al., 1985; Bergant et al., 2008). On the structural side, there can be higher and lower stresses in the pipe and also the structural frequencies change due to FSI (Heinsbroek and Tijsseling, 1994; Heinsbroek, 1993; Diesselhorst et al., 2000). Frequency shifts have also been described in analytical models for coupled fluid–structure systems (Goyder, 2007; Moussou et al., 2000). In fact, it is not really a frequency shift because the uncoupled case does not exist. The reference case is an idealised one.

Overall the effects of FSI can be significant, but a general recommendation to perform water hammer calculations with two-way FSI would be cumbersome due to the high computational costs and a large number of unknowns, e.g. support rigidities and flange joints.

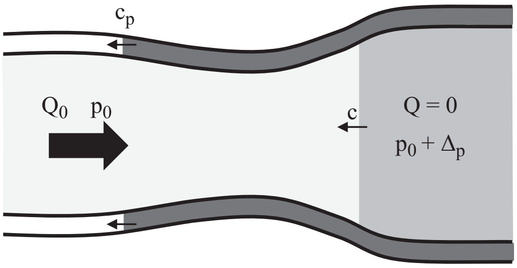

Fig. 1. Poisson coupling in a pipe section.