Twenty years of FSI experiments in Dundee

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Abstract

Waterhammer with fluid–structure interaction (FSI) with or without cavitation can be a rewarding subject for academic research. This paper gives an overview of two decades of experimental work at the University of Dundee. The experiments concern impact tests on water-filled steel-pipe systems. The aim of the research has been to produce high-quality experimental data for vibrating pipe systems with strong liquid–pipe coupling. One set of new data, namely the natural frequencies of a T-shaped pipe system, is presented. These, and other published data, will be made freely available at www.win.tue.nl/fsi

Keywords: FSI; Waterhammer; Cavitation; Pipe; Impact; Experiment

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1. Introduction

1.1. Background

Païdoussis' fluid–structure interaction (FSI) encyclopaedia [1,2] gives an exhaustive treatment of the dynamics of pipes carrying steady or harmonically perturbed flow. This subject is rich with interesting fundamental problems and solutions. Our work on waterhammer with FSI, categorised by Païdoussis under 'unsteady FSI phenomena', is academically less exciting but of considerable importance in industrial piping systems. It was motivated by incidents and accidents caused by waterhammer in which displacement and failure of pipes and supports occurred. Research in this area has been driven largely by safety requirements in the nuclear and chemical industries [3,4].

1.2. Goal of experiments

The original objective of the research was to design and build a test rig for clean and accurate experiments on vibrating pipes with strong liquid–pipe coupling. By 'clean', we mean the avoidance of complications encountered in conventional reservoir–pipe–valve systems, such as unknown support conditions, unsteady valve behaviour, non-constant reservoir pressure, disturbing pump vibration, de-aeration, etc. The resulting experimental results serve as benchmark data for the validation of theory and software.

1.3. A little bit of history

There are no immediate plans for future experiments so this is a good time to look back. Alan Vardy initiated FSI research in Dundee. In 1984, an undergraduate student undertook preliminary tests with a water-filled pipe dropped vertically onto a steel base. In 1985, David Fan took over, working initially with the vertical pipe but subsequently conducting many experiments with pipes suspended horizontally on long steel wires. In 1989 and 1990, Arris Tijsseling of Delft University visited Dundee to carry out cavitation tests; in 1993, he moved to Dundee. Zhang Lixiang of Kunming University was visiting professor in 1994 and in 1997. In 1998, Della Leslie extended the originally planar systems to three dimensions. Throughout, valuable technical assistance has been given by many people, of whom Ernie Kuperus and Colin Stark deserve special thanks.

2. Overview of experimental results

Figure 1 shows seven test systems, each composed of steel pipes of 60 mm outer diameter and 4 mm wall

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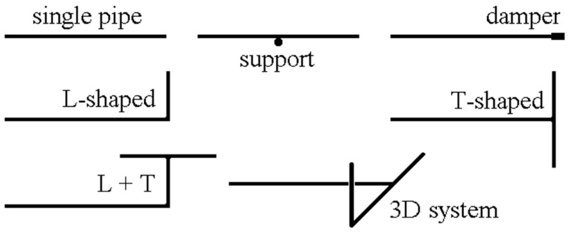

Fig. 1. Schematic representation of laboratory pipe systems.

Table 1
Key publications of experimental results

	Vibration		Impact		
Configuration	Transient	Free	Axial	Lateral	Cavitation
Single pipe	[5–7]	[8]	[5–8]	[6,8]	[7]
Support	[9]		[9]		
Damper	[10]		[10]		
L-shaped	[11]	[12]	[11,12]	[12]	[11]
T-shaped	[13,14]	herein	[13,14]		[14]
L + T	[15]	*	[15],*		
3D system	*	*	*		

* To be published.

thickness. One pipe is 4.5 m long; the others are 1.3 m long. The systems, suspended on wires, are closed at their ends and filled with pressurised tap water. Excitation is by the axial or lateral impact of a 5-m long, 51-mm diameter steel rod on a closed end of the long pipe. Pressures, strains and structural velocities are measured at several positions along the pipes.

The dynamic behaviour of the systems is governed by axial and lateral waves in the pipe walls and by pressure waves in the liquid. The vertical pipe in the three-dimensional (3D) system gives rise to torsional waves and out-of-plane vibration. Strong liquid–pipe coupling occurs at the closed ends, at the elbow and at the tee. Weak coupling exists along the pipes due to axial–radial Poisson contraction/expansion. There is little damping in the system, except when introduced deliberately through a support or a damper. Transient cavitation occurs in cases where the initial static pressure of the liquid is sufficiently low. *Transient* vibration is recorded in tests of typically 30 ms duration at sampling intervals of 8 μs. *Free* vibration tests are typically of 1.5 s duration, with sampling intervals of 100 μs.

Table 1 lists key publications presenting the experimental data. All but one of these contain numerical simulations confirming (and interpreting) the measurements.

3. Natural frequencies of water-filled T-shaped system

The fingerprint of a structure is formed by its natural frequencies, and FSI is known to change these natural frequencies [4,8]. An accurate measurement of the natural frequencies of the basic pipe configurations, single, L-shaped and T-shaped, therefore is essential in FSI research. The natural frequencies of a single pipe and an L-shaped pipe have been published [8,12]. Previously unpublished natural frequencies of the T-shaped system specified in Table 2 are given in Table 3. These have been derived from axial impact tests in which the long pipe is assumed not to vibrate laterally. A typical spectrum is shown in Fig. 2.

4. Conclusion

This paper summarises the authors' experimental research on unsteady FSI phenomena in liquid-filled pipe systems. It lists key publications and presents one

Table 2
Measured properties of T-shaped pipe system

Pipe lengths (m)	Inner radius (mm)	Wall thickness (mm)	Young modulus (GPa)	Poisson ratio kg/m^3	Mass density	Impact plug mass (kg)	End cap masses (kg)	T-junction mass (kg)
4.51 1.34 1.34	26.01	3.945	168	0.29	7985	1.30	0.32	1.06

Table 3
Measured natural frequencies (in Hz) of symmetric water-filled T-shaped pipe system

26	115	152	233	345	381	470	478	579	687	757	796	871	925	986

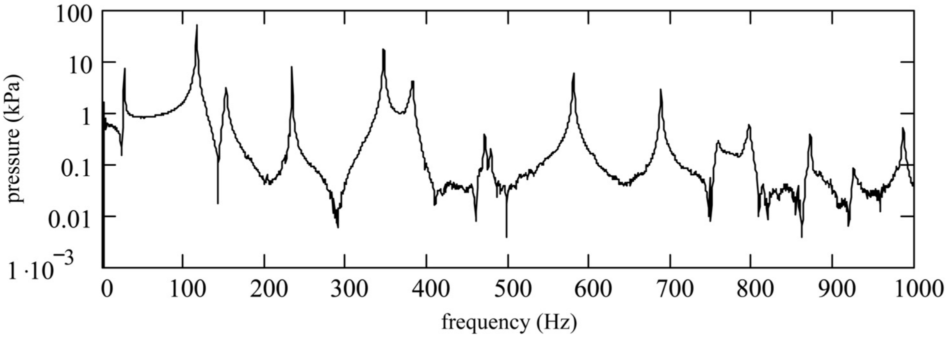

Fig. 2. Measured pressure spectrum.

omission in published data, namely the natural frequencies of a water-filled T-shaped pipe system. These frequencies embrace the significant influence of FSI.

The resulting data have the special feature of exhibiting coupling phenomena without the complications that arise in experiments on pseudo-'real' systems, thereby making the data suitable for academic validation purposes. To facilitate its use for this purpose, many data are available freely on a website at the Technical University of Eindhoven: www.win.tue.nl/fsi This site, initially developed in Dundee by Vardy, Leslie and Tijsseling, is now supported exclusively by Tijsseling. Contributions to the site will be welcome from any competent source.

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