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An overview of fluid-structure interaction experiments in single-elbow pipe systems

by

A.S. Tijsseling

Centre for Analysis, Scientific computing and Applications
Department of Mathematics and Computer Science
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven, The Netherlands
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Arris S. TIJSSELING
Department of Mathematics and Computer Science
Eindhoven University of Technology
P.O. Box 513, 5600 MB Eindhoven
The Netherlands
e-mail: a.s.tijsseling@tue.nl

ABSTRACT

Sixteen experiments carried out on liquid-filled L-shaped pipe systems are reviewed. The purpose of nearly all the experiments was to study fluid-structure interaction (FSI). The influence of loose elbows on the dynamic behaviour of liquid-filled piping systems is clearly demonstrated. This report has an educational character regarding the execution of laboratory experiments where FSI is involved.

INTRODUCTION

Fluid-structure interaction. Elbows are key elements in pipe systems (Fig. 1). They are needed to guide fluid from one place to another and they determine the static and dynamic behaviour of fluid and piping. Acoustic pressure and flow perturbations and associated mechanical vibrations are essential ingredients in integrity and safety studies. Short-term events − like hydraulic transients − may lead to unacceptably high fluid pressures and long-term events − like acoustic resonance − may involve structural fatigue and noise issues. The mobility of elbows, U-bends, tees and closed ends, is the strongest mechanism coupling fluid and pipe dynamics. Fluid-structure interaction (FSI) is the keyword here. The significance of FSI is fully recognized and the subject has reached a certain maturity [1-3].

Fig. 1 Multi-elbow pipe systems.

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Experiments. Physical experiments are prerequisite for demonstrating the importance of FSI and they are essential for the validation of theory. Clean laboratory tests are best for validation purposes, whereas "unclean" field measurements are intended to confirm FSI relevance in practice and to back up trouble-shooting and post-accident analyses. Time-domain experiments are commonly related to waterhammer events and structural impacts, whereas frequency-domain experiments usually focus on resonance, excessive vibration, noise and fatigue. The outcomes of mathematical models and numerical simulations are indispensable for a proper interpretation of the experimental results. There must be no room for speculation: either additional measurements or deeper theoretical analyses should throw the necessary light. Scale and scaling are issues that determine to which extent the laboratory set-up represents the real world and which tell what the dimensionless parameters are that describe the system. Outliers in measured data are more often than not left out, not reported, or simply ignored, which is not a wise thing to do if one wants to discover new phenomena. Good experimental data lasts forever and therefore needs to be reported clearly and completely. This general statement especially applies to the near future where "Open Access and Retrievable Experimental Data" will be the standard. The latter is useless without comprehensive and accurate documentation. Plagiarism and cheating is another issue nowadays, and therefore the possibility to check, repeat and reproduce published experimental data is a must (as it should be).

Review. As said, good experimental data are of "eternal" value and the aim of this report is to provide an overview of good FSI experiments that have been conducted and documented in the past half a century. Sixteen experiments have been selected which may not fall into oblivion. The relevant parameters of the eight frequency-domain and eight time-domain experiments are conveniently arranged in two tables A and B, respectively. The (obvious) requirements for conducting FSI experiments are summarized. Common features in all considered experimental results and conceivable FSI rules are to be looked for. The review is limited to systems with a single elbow (L-pipes). Straight pipes, branched systems (T-pipes), two-elbow systems like U-bends and Z-shapes, and extended systems that are closer to industrial practice are most interesting but not part of this dedicated review. Theory is not presented herein.

REQUIREMENTS FOR FSI EXPERIMENTS

Experimental researchers know what the requirements for quality experiments are. Here the focus is specifically on FSI experiments with elbows in an attempt to assist people in setting up new tests without overlooking relevant issues and thereby preventing errors made in the past. This section is also an introduction to the review of the experiments described in the next section.

One obvious requirement is to measure both in fluid and structure. A second obvious requirement is to be precise and complete in the documentation. The following list of questions may seem trivial for elbow experiments and the corresponding mathematical models, but they are not so in view of the likely sensitivity to details of the system dynamics. Where does the elbow start and where does it end? Are pipe lengths including or excluding the elbow? How (tight) is the elbow connected to the adjacent pipes? What are the mass, stiffness and moment of inertia of the elbow? What is the radius of curvature? What is the ovalness and ovalisation factor of the elbow? What are the masses of flanges and attached instrumentation? What is the mass, stiffness and damping of anchors and other types of support? How rigid is the connection of a pipe wall with a liquid supply tank? What causes damping in the system and can the distinguished mechanisms be quantified? How good is the instrumentation? Can one rely on manufacturers' data? Are material properties accurately measured or just taken from handbooks? Can steady-state or statically determined values be used for modelling dynamic events? Can temperature effects be ignored? Could there be any entrapped air in the system? Is the air content of water important and measured? Is the L-shaped system deformed in its (hydro-)static state? Does the excitation source act on the fluid, the structure or (unintentionally) on both? Are there unwanted disturbances generated by e.g. pumps or orifices? Have data been filtered (by data-acquisition system or by post-processing)? Have outliers been ignored (e.g. famous Nikuradse story [4])? Are the tests fully repeatable?

One should realize that even more (accurate) data are needed for the validation of 3D mathematical models than for the conventional 1D models. Sometimes it is difficult to acquire all required system data of reported experiments, because the relevant information is spread over several publications, available only in difficult-to-obtain reports, or simply absent. Typing errors in documentation can be most annoying.

FSI EXPERIMENTS IN L-SHAPED PIPES

All sixteen experiments considered herein are based on (variations of) one of the four configurations shown in Fig. 2. Figure 2a represents the most practical case, where the elbow is rigidly supported at certain distances upstream and downstream along the pipeline. Figure 2b shows the situation where one leg is allowed to move axially. Figure 2c is the cantilever used in a number of experiments, with a liquid free-surface at the top of (or somewhere in) the vertical leg. Figure 2d depicts an entirely closed system, where – in contrast to the systems (a), (b) and (c) − strong FSI (junction coupling) not only takes place at the elbow, but also at the closed ends. The systems are excited either through fluid (valve manoeuvre, underwater loudspeaker) or structure (mechanical shaker, projectile impact). The experiments are briefly discussed in chronological order. The Appendices A and B contain the corresponding tables with system properties and peculiarities, where data has been taken from the publications indicated in the first column. Missing or additional data can often be obtained from M.Sc. and/or Ph.D. theses and from departmental and/or company reports.

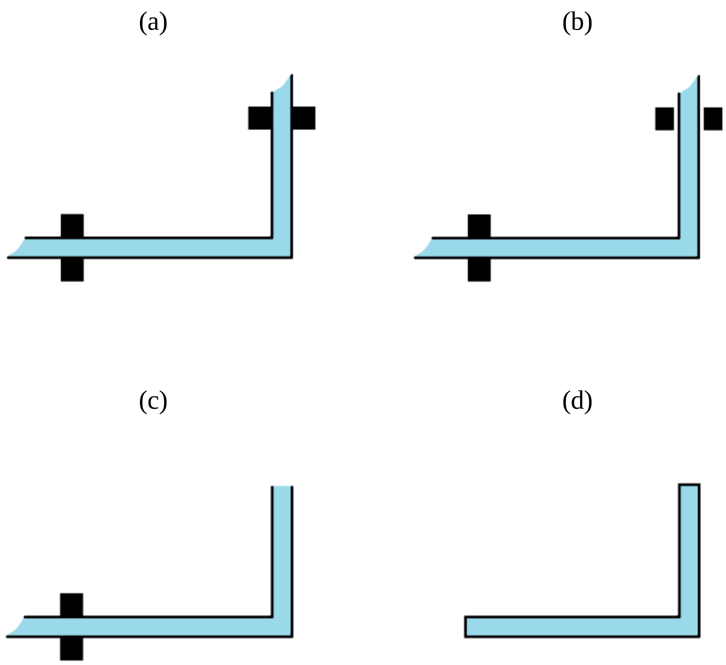

Fig. 2 Basic configurations for unrestrained right-angle FSI tests: **(a)** Wood and Chao, 1971; Wiggert et al. 1985; **(b)** Blade et al., 1962; **(c)** Davidson and Smith (1969); **(d)** Tijsseling et al., 1996; Steens and Pan, 2008.

[A1] Blade, Lewis and Goodykoontz's (1962) laboratory setup is schematised in Fig. 2b. It is an unrestrained system resting on a bed of about 66 transverse wires. Axial motion was allowed for the downstream leg, but its transverse motion was suppressed. The motivation for the study came from lightweight fluid systems for missile and space applications, where sections of the pipeline may vibrate longitudinally as a whole in response to unbalanced pressure forces.

[B1] Swaffield's (1968-1969) comprehensive experimental investigation is most interesting, because it provoked much discussion. The question he tried to answer was: does a pressure wave reflect partially but significantly from a rigidly supported elbow? His answer was yes, say 6% for a single right-angled bend. In the discussion of his paper by eight peers (the pages 609-614) his experimental results were either doubted or a plausible explanation was sought for. One of the discussers correctly stated: any change brought about by the bend should be negligible if the wave front is long compared with the length of the bend, which is true in most practical systems. Another discusser quoted Rayleigh [5]: considering the wave propagation in a curved pipe, when the diameter (of the pipe) is very small compared to the wavelength, then the wave equation in terms of the curved pipe axis is the same as if it were straight. Later on, Swaffield admitted (in a private communication with D.H. Wilkinson) that his measurements suffered from the ignored motion of "fixed" points, as noted by Wilkinson [6]. This evidently demonstrates how difficult it is to have rigid supports and that "rigidity" in FSI experiments should always be checked one way or the other.

[A2] Davidson and Smith's (1969) experimental data have been used by many others, partly because it has simple boundary conditions. The L-shaped pipe is placed in a vertical plane and attached as a cantilever to a wall (Fig. 2c). There are no additional supports affecting the measurements and the downstream termination simply is a liquid free-surface. Unfortunately, the experimental results are invalid due to ("unknown") flexibility of the assumed rigid cantilevered support [7]. The motivation for the study was pump noise transmission in piping systems. This had previously been treated as separate problems of liquid-borne and structure-born noise, although significant intermedia coupling is present in most pipe configurations.

[B2] Wood and Chao's (1971) system does not allow for much pipe motion (Fig. 2a). To quote the authors: "When the bend was not constrained locally, it was completely restrained at the terminal points of the pipeline. For this case the bend, in fact, was quite restrained and, to the hand, felt very rigid. It was observed that the maximal displacement of the bend was only 1.3 mm. This small movement, however, caused the significant effects noted.". One of the "significant effects" is a 14% increased transient pressure (compared to tests with a locally restrained bend) for a 60° sharp bend. The constrained-bend tests contradicted with Swaffield's (1968-1969) findings: the transient pressure lost at the fixed bend was smaller than 1% for all bend angles (30, 60, 90, 120 and 150 degrees). D.J. Wood is one of the FSI pioneers and therefore quoted here: "The high pressures generated by the rapid closure of a valve result in large forces which must be resisted by the structure supporting the pipeline. Great care is usually taken by experimental investigators to eliminate this motion so the results obtained are free from the effects of the motion. However, it is improbable that actual pipelines are ever anchored sufficiently to eliminate entirely motion due to a waterhammer surge.".

[A3] Two interesting papers appeared in 1978 at one of the well-known (within the FIV community) "Keswick" conferences. Fahy and Firth (1978) presented a limited amount of measured data. High-frequency excitation caused pipe ovaling and higher modes of wall vibration. No attempt was made to provide any one particular form of ideal structural boundary condition. The authors stated that the presence of bends increases the efficiency with which disturbances (generated by pumps) can excite into resonance beam-type flexure of the pipe lengths, and may also induce the excitation of higher-order modes in which cross-sectional distortion occurs.

[A4] Wilkinson (1978) presented some experimental data obtained by Beesley (Risley Nuclear Laboratory) in 1976. FSI due to bend motion increased the acoustic resonance frequency significantly (from 500 Hz to 600 Hz).

[B3] A-Moneim and Chang (1979) used a gun to generate a 150 bar pulse of 3 ms duration. The travelling pulse caused plastic wall deformation in thin-walled nickel pipes. Experimentally, although the end and elbow flanges were anchored to the ground to limit their motion, some of the incident pulse energy was expended in axially expanding the downstream pipe as the pulse hit the blind flange. An 18% effect of the elbow (on the incident pressure pulse) was indicated, similar to Swaffield's (1968-1969) findings, and this was attributed to ovaling and narrowing of the elbow, but not to elbow displacement. The pipeline was extensively instrumented and, with respect to this, the importance of pre-test analysis of experiments in locating the instrumentation was demonstrated (with hindsight). The aim of the experimental program was software validation. The software was used to predict the severity and location of critical regions in real systems.

[B4] Hu and Philips (1981) applied external impact with a high-speed projectile generating a short pressure pulse of 0.2 ms duration. They used hydraulic fluid (oil) as working fluid to avoid the possible entrainment of air. It was not (clearly) indicated how the L-pipe was anchored.

[B5] The paper by Wiggert et al. (1985) is an excellent introduction to the subject in which it is experimentally demonstrated that transient pressure in piped liquid is a function of structural restraint at elbows. First, it is verified that there is no pressure reflection from an immobile elbow. Second, for the case of unrestrained elbow motion, an initial increase in the liquid pressure was observed due to a precursor stress wave in the pipe wall that pulled the elbow back (pumping action); the later arrival of the liquid pressure wave at the elbow caused a decrease in pressure (storage action).

[A5] Tentarelli (1990) carried out five precise FSI experiments, one of them being the cantilevered L-tube of Fig. 2c, but with a closed downstream end. Frequency-domain measurement-error was analysed in detail since this was of particular importance near (anti-)resonance. The experiments were with tiny tubes.

[A6] De Jong (1994, 1995) also used the configuration of Fig. 2c, but with heavy masses attached to the ends. The bottom mass behaved as a rigid body; the top mass was there to avoid direct excitation of the pipe wall when using an underwater loudspeaker near the free surface. In the elbow tests the top mass was excited by a shaker.

[A7] Svingen (1996ab) built an extremely slender and flexible L-shaped system that was excited by a specially designed rotating disk that partly covered a rectangular orifice. The system was so slender that – in addition to unintentional valve motion – sagging was an issue.

[B6] Tijsseling et al. (1996) presented experimental data on a freely suspended, fully closed, L-pipe (Fig. 2d) with and without cavitation in the liquid. The system was excited by the structural impact of a long solid rod. Tijsseling and Vaugrante (2001) listed the measured natural frequencies of the same L-pipe.

[A8] Caillaud et al. (2001) studied the modal behaviour of an L-shaped system with an open end (Fig. 2c), where the water level in the vertical leg was varied. Much attention was paid to the design of the clamped end (since nothing is perfectly rigid), the pressure taps and the de-aeration of the water (by waiting one month before doing a test).

[B7] Steens and Pan (2008) used a similar set-up as Tijsseling et al. (1996) (Fig. 2d) but with a pendulum impact-hammer that produced a short duration pulse in both the liquid and the pipe wall.

[B8] The experimental facility of Altstadt et al. (2008) has a closed downstream end that is hit by an accelerating column of liquid. Unlike Swaffield (1968-1969), they concluded that "pressure waves travel without any disturbance through pipes, regardless of changes of direction" (i.e., no wave reflections at fixed elbows). Only FSI can cause such disturbances (due to free elbows). The incentive of their study was pipe impact loads and responses due to (steam) condensation-induced waterhammer in (nuclear) power plants.

CONCLUSION

Carrying out and documenting laboratory experiments is difficult and time consuming. Large amounts of data have to be analysed and presented to others in a compact way. In general this is more difficult than running computer simulations, and more expensive. Published experimental data last for years and will therefore be used by many others. There is a well-known adage within the scientific community that everyone trusts experimental data, except the person who carried out the actual measurements. Therefore published experimental results should be treated with care. (With computer simulations it is the opposite: no one believes calculated results, except the person who proudly produced them.) The present review focussed on one specific and (in principle) well-defined type of FSI experiment and looked at what has been achieved and how well-documented published data are. The review is intended to be of help in selecting measured data for validation purposes and for setting up new experiments. It is also intended to not-forget valuable experimental studies.

If supported rigidly, an elbow causes no appreciable alteration of the pressure transient generated by for instance rapid valve closure. However, if the elbow support is relaxed, a significant alteration is observed. For the single-elbow systems considered herein one general conclusion that may be drawn (with reservation) is that a positive pressure wave loses pressure when it arrives at an elbow, because it makes the elbow move away, thereby creating additional storage for the compressed liquid. As a common exception, precursor stress waves in the pipe wall – caused by and traveling ahead of the main pressure wave – may pull the elbow back and create additional pressure as a result of a pumping action. Joukowsky overshoots due to FSI of between 7% [1] and 33% [1] have been observed in all time-domain experiments. Significantly changed resonance frequencies because of elbow vibration have been observed in all frequency-domain experiments. It will be difficult to find general rules for multi-elbow systems, but reliable FSI theory and corresponding software exists for predictions as accurate as the input data allows. The validation of the underlying FSI theory is thanks to the hard work of all the researchers mentioned herein. Much of their data is still used for validation purposes today.

As a last note it is to be said that most waterhammer experiments include undesired FSI effects. In that sense Holmboe and Rouleau [8] were so wise to embed their entire laboratory system in solid concrete.

[1] to be double checked from Refs [B1]-[B8]

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APPENDIX A − Table A Frequency-domain experiments.

Ref.	L_1 L_2 (m)	D (mm)	e (mm)	Fluid	Solid	BC fluid u / d	BC solid u / d	Elbow orientation, type and restraint	Type and number of inter-mediate supports	Excitation	Vibra-tion (Hz)	Instr.	Comments
[A1]	10.4 10.4	22.1	1.65	JP-4 F-40 avtag fuel	steel	open P open orifice	fixed axially free laterally fixed	hor. mitre free $R_c/D \approx 1$	resting on 66 hor. wires	valve	forced 0.5 - 75	2 PT 2 FM 1 DT	rigid pipe motion of downstream leg, measured suspension stiffness, varied orifice impedance
[A2]	0.91 0.91	114.3 outer	?	oil	copper- nickel	closed piston open, free surface	“fixed” free	vert. mitre free	none, cantilever	piston	forced 20 - 2000	2 PT 6 acc.	“fixed” point moved: see [7] Brown and Tentarelli (1988, p. 148)
[A3]	1.1 1.1	60.2	1.63	water	steel	closed piston open special	clamp clamp	hor. curved free $2.1 < R_c/D < 4.1$	none	piston or external shaker	forced 150 - 3200	>4 acc.	entire L-pipe immersed in water reflection-free downstream BC
[A4]	0.25 0.65	70 outer ?	0.9	water	?	closed? closed?	mass free	vert. mitre free 0.14 m length	none?	shaker	forced up to 1100	?	
[A5]	1.16 0.64	5.1	1.25	hydr. oil	steel	open closed	150 kg clamp free	vert. 0.15 kg elbow of 75 mm length	none	valve	forced up to 2000	1 PT 1 acc.	measured lumped masses and rotary inertia
[A6]	1.45 1.41	150	4.5	water	steel	closed open, free surface	572 kg mass 176 kg mass	vert. elbow $R_c/D = 1.6$	none	shaker	forced 20 - 600	1 PT 4 acc. 1 FT	measured lumped masses and rotary inertia, measured stiffness of bolted flanges
[A7]	8.5 11.15	80	1.5	water	steel	open P open	rigid rigid	vert. elbow of 0.2 m length ff = 10.7	none	rotating valve	forced up to 300	2 PT 2 acc.	initial deformation of L-shape because of slenderness, unintentional valve motion [A7a] (p.76)
[A8]	1.6 1.5	93.3	4.2	water	steel	open closed	fixed free	vert. elbow $R_c/D = 1.4$	none	shaker or gun	1 - 500	PT 22 acc.	variable water level in vertical pipe

acc. = accelerometer	L = pipe length
BC = boundary condition	LDV = laser-Doppler vibrometer
d = downstream	P = constant pressure
D = pipe inner diameter	PT = pressure transducer
DT = displacement transducer	R_c = radius of bend curvature
e = pipe wall thickness	S = solid or structure
ff = flexibility factor	SG = strain gauge
F = fluid	Temp. = temperature
FM = flow meter	u = upstream
FT = force transducer	V = constant velocity
Instr. = Instrumentation	vert. = vertical
hor. = horizontal	> = more than
hydr. = hydraulic	? = omission or unclearness in reported work

APPENDIX B – Table B Time-domain experiments.

Ref.	L_1 L_2 (m)	D (mm)	e (mm)	Fluid	Solid	BC fluid u / d	BC solid u / d	Elbow orientation, type and restraint	Type and number of intermediate supports	Excitation (ms)	Initial flow velocity (m/s)	Instr.	Comments
[B1]	6.7 5.5	38.1 - 76.2	1.6 - 6.35	water	polythene, steel, copper, aluminium	open closed	free elbow fixed (1 jack)	45° - 180°, hor. mitre, hor. curved bends $0.85 < R_c/D < 5.0$, rigid (2 jacks)	none	valve closure 2 - 5	0.6 - 2.4	4 PT Temp.	interesting discussion [B1, pp. 609-614], unwanted pipe motion: see [6] Wilkinson (1980, p. 197)
[B2]	6.1 6.1	12.7 outer	?	water?	copper	open P closed	fixed fixed	30° - 150°, hor. mitre rigid and free	none	valve closure 2	2 - 3	2 PT 1 acc. 1 DT	no rigid motion, experiment successfully simulated in [9] by Lavooij and Tijsseling (1989)
[B3]	1.5 1.5	72.9	1.65	water	nickel	closed closed	fixed fixed	hor. 114.3 mm, D = 70.6 mm, R_c/D = 1.6, rigid	none	gun: 150 bar pulse 3	0	18 PT 20 SG	slightly oval elbow with inner diameter smaller than that of the two pipes, precursor effects
[B4]	1.0 1.0	21.2? and 19.05 outer?	2.54 ?	hydr. oil ?	aluminium	closed closed	fixed? free?	? R_c/D = 6	?	pellet impact 0.2	0	1 PT >8 SG	static PT?
[B5]	7.7 12.3	26	1.27	water	copper	open P closed	fixed fixed	hor. R_c/D = 0.8	wires	valve closure 4	1.2?	2 PT 2 acc.	Case B 0.5 mm elbow displacement
[B6]	4.51 1.34	52	3.9	water	steel	closed closed	free free	hor. 0.88 kg	3 wires	rod impact 0.15	0	6 PT 20 SG 1 LDV	free vibration up to 500 Hz in [B6b]
[B7]	1.5 6.5	34.85	3.2	water	steel	closed closed	free free	hor. R_c/D = 2.2	4 wires	impact hammer pulse 1-2	0	2 PT 4 acc. 1 FT	
[B8]	1.8 (or 1.0) 1.5	207	6.0	water	austenitic steel	open P closed	fixed fixed or free	vert. elbow R_c/D = 1.5	none (or fixed valve)	valve opening 20 - 200	3 - 17	>8 PT 1 acc. >28 SG needle probes	it is not clear how the closed end and the midway valve are structurally fixed; the mass of the valve is not specified; needle probes are used to measure void fraction; "wrong" glue has been used for SG; residual air may be present at the dead end

acc. = accelerometer	L = pipe length
BC = boundary condition	LDV = laser-Doppler vibrometer
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e = pipe wall thickness	S = solid or structure
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F = fluid	Temp. = temperature
FM = flow meter	u = upstream
FT = force transducer	V = constant velocity
Instr. = Instrumentation	vert. = vertical
hor. = horizontal	> = more than
hydr. = hydraulic	? = omission or unclearness in reported work

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Ontwerp: de Tantes,
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