Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.jzus.zju.edu.cn; www.springerlink.com
E-mail: jzus@zju.edu.cn

**Mini-review:**

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

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Received Oct. 8, 2018; Revision accepted Mar. 9, 2019; Crosschecked Mar. 19, 2019

**Abstract:** Fluid-structure interaction (FSI) in vibrating pipe systems is a phenomenon that finds its source, among other mechanisms, in unbalanced pressure forces acting on loose elbows. The subject has received considerable attention in theoretical research and practical engineering. Sixteen laboratory experiments carried out on liquid-filled single-elbow (L-shaped) pipe systems are reviewed herein. Eight frequency-domain and eight time-domain experiments are concisely described in the Appendices A and B. The purpose of nearly all experiments was to study FSI and demonstrate the influence of moving elbows on the dynamic behavior of liquid-filled piping systems. This historical review has an educational character with regard to the execution of laboratory experiments featuring FSI.

**Key words:** Fluid-structure interaction (FSI); Laboratory experiment; Pipe elbow; Pipe bend; Elastic liquid
https://doi.org/10.1631/jzus.A1800564   **CLC number:** O35

## 1 Introduction

Elbows are key elements in pipe systems. They are needed to guide fluid from one place to another, and they determine—together with the supports—the static and dynamic behavior of structure and fluid. Acoustic flow and pressure perturbations as well as the associated mechanical vibrations are necessary components in integrity and safety studies. Short-term events like hydraulic transients may lead to unacceptably high fluid pressure, whereas long-term events like acoustic resonance may involve structural fatigue and noise. The mobility of elbows, U-bends, T-branches, and closed ends, is the strongest mechanism coupling fluid and pipe dynamics. Fluid-structure interaction (FSI) is the keyword here. The significance of FSI has been fully recognized and research on the subject has reached a certain level of maturity (Tijsseling, 1996; Wiggert and Tijsseling, 2001; Li et al., 2015; Moore, 2016; Ferras et al., 2018).

Physical experiments are a prerequisite for demonstrating the importance of FSI, and at the same time are essential for the validation of theory. Well-controlled laboratory tests without undesirable complications are best for validation purposes, whereas industrial measurements in situ are intended to confirm the practical relevance of FSI, and backup trouble-shooting and post-accident analyses. Time-domain experiments are commonly related to water-hammer events and external 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 any experimental results. There must be no room for speculation: Either additional measurements or deeper theoretical analyses should be used to

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eliminate uncertain factors. Scale and scaling, based on dimensionless parameters used to design experiments, determine the extent to which the laboratory setup represents the real world. Inexplicable outliers in measured data are more often than not left out, not reported, or are simply ignored, which is not advisable if one wants to discover new phenomena. Good experimental data have a long tenability and, therefore, need to be reported clearly and completely. This general statement applies especially well to the near future, when open access and retrievable experimental data will be the standard. The latter is useless without comprehensive and accurate documentation. Plagiarism and cheating in research are important issues, and therefore published experimental data must be capable of being verified, repeated, and reproduced. Already published work might need to be retracted if the data do not pass this test.

As mentioned above, well-measured data have eternal value, and the aim of this paper is to provide an overview of profound FSI experiments that have been conducted and documented in the past half a century. To perpetuate them, 16 experiments were selected to this end. The relevant parameters of the eight frequency-domain and eight time-domain experiments are arranged in two Tables A1 and B1, respectively. The (obvious) requirements for conducting FSI experiments are summarized. Features common to all the considered experimental results and conceivable FSI rules are sought. 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 layouts are most interesting, but are not part of this dedicated review. Theory is not presented herein.

## 2 Requirements for FSI experiments

Experimental researchers know the requirements for quality measurements. The focus here is on FSI experiments with elbows to offer advice to experimenters in setting-up new tests without overlooking any relevant issues and thus preventing errors made in the past. This section is also an introduction to the review of the experiments described in the next section.

One basic requirement is to measure in both fluid and structure. The second is precision and completeness of the documentation. The following list of questions may seem trivial for elbow experiments and associated mathematical models, but they are not in view of the likely sensitivity of the system dynamics to subtle details.

Where precisely does the elbow start and end? Do the lengths of the pipe and the liquid include or exclude the elbow? How (tightly) is the elbow connected to adjacent pipes? What are the mass, stiffness, and moment of inertia of the elbow? What is its radius of curvature? What are the ovalness and ovalization factors of the elbow? What are the masses of flanges and the attached instrumentation? What are the mass, stiffness, and damping of the anchors and other types of support? Can pipes slide on supports? How rigid is the connection of the pipe wall with the liquid reservoir? What causes damping in the system, and can it be quantified? How good is the instrumentation, for example, response times and eigenfrequencies of sensors and amplifiers? Can one rely on the manufacturers' data? Are the material properties accurately measured or simply taken from handbooks? Can steady-state or statically determined quantities be used for modeling dynamic events? Can the effects of temperature be ignored? Can there be any trapped air in the system? Is the air content of water important and, if so, measured? Is the L-shaped system deformed (sagging) in its (hydro)static state? Does the source of excitation act on the fluid, the structure, or (unintentionally) both? Does the source interact with the system? Are there unwanted disturbances generated by, e.g. pumps or orifices? Is the sampling rate high enough? Have the data been filtered (by instrumentation or by post-processing)? Have outliers been ignored (e.g. the famous Nikuradse story (Rouse, 1991))? Are the tests fully repeatable?

Even more (and more accurate) data are needed for the validation of 3D mathematical models than for the conventional 1D models describing piping systems. It was sometimes difficult to acquire all the required system data of the reported experiments because the relevant information was spread over several publications, available only in difficult-to-obtain reports, or was simply absent. Photos of the apparatus can be very illuminating. Typing errors in documentation can be most annoying. The error estimates of (all) the physical data are usually not given, so that uncertainty quantification becomes a challenging task.

## 3 FSI experiments on L-shaped pipes

All 16 experiments considered herein were based on (variations of) one of the four configurations shown in Fig. 1. Fig. 1a represents the most practical case, where the elbow is rigidly supported at certain distances upstream and downstream along the pipeline. Fig. 1b shows the situation where one leg is allowed to move axially, and Fig. 1c is the cantilever used in a number of experiments, with a liquid free-surface at the top of (or somewhere within) the vertical leg. Fig. 1d depicts an entirely closed system, where, in contrast to the systems in Figs. 1a–1c, 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 maneuver, underwater loudspeaker) or structure (mechanical shaker, projectile impact). The experiments are briefly discussed in chronological order. Appendices A and B contain the corresponding Tables A1 and B1 with the system properties and peculiarities, where data were taken from the publications referred to in the second column of the table. Missing or additional data can often be obtained from MS and/or PhD theses, and from departmental and/or company reports. The labels [A] and [B] indicate experiments in the frequency and time domain, respectively.

**[A1]** Blade et al. (1962)'s laboratory setup is schematized in Fig. 1b. It is an unrestrained system resting on a bed of approximately 66 transverse wires. Axial motion was allowed for the downstream leg, but its transverse motion was suppressed by a flexible diaphragm. The excitation was sinusoidal flow perturbation at the upstream leg. 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 (1968)'s comprehensive experimental investigation is most interesting because it provoked much discussion. The question he tried to answer was: Does a pressure wave in the fluid 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 (pages 609–614), his experimental results were either doubted or a (more) plausible explanation was sought for them. One of the peers correctly

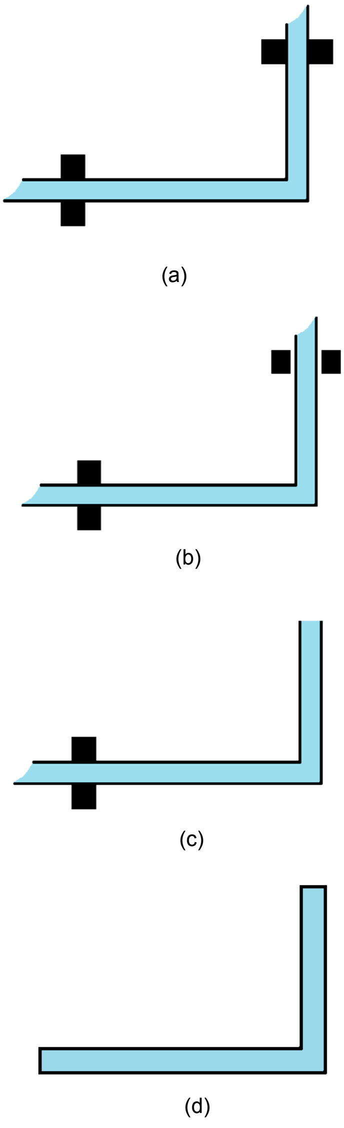

**Fig. 1 Basic configurations for unrestrained right-angle FSI tests: (a) Wood and Chao, 1971; Wiggert et al., 1985; (b) Blade et al., 1962; (c) Davidson and Smith, 1969; (d) Tijsseling et al., 1996; Steens and Pan, 2008**

claimed that any change brought about by the bend should be negligible if the wave front is long compared with the length of the bend, as this is true in most practical systems. Another discusser quoted Rayleigh (1894) and claimed that considering wave propagation in a curved pipe, when the diameter (of the pipe) is very small compared with the wavelength, 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 ignored the motion of structurally “fixed” points, as noted by Wilkinson (1980). This demonstrates how difficult it is to have fully rigid supports, and that “rigidity” in FSI experiments should always be checked one way or the other. Adding mass is a better option to prevent the transient motion of bends and supports.

**[A2]** Data measured by Davidson and Smith (1969) have been used by many researchers, partly because their experiment has simple boundary conditions. The L-shaped pipe was placed in a vertical plane and attached as a cantilever to a wall (Fig. 1c). There was no additional support affecting the measurements, and the vertical pipe’s end simply had a free surface. Unfortunately, the experimental results were invalid due to the (unknown) flexibility of the cantilevered support which was assumed to be rigid (Brown and Tentarelli, 1988). The motivation for the study was the transmission of pump noise in industrial piping systems. These had previously been treated as separate problems of liquid-borne and structure-borne noise, although significant inter-media coupling is present in most pipe configurations.

**[B2]** Wood and Chao (1971)’s system does not allow for much pipe motion (Fig. 1a). The authors stated: “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” mentioned by the authors was a 14% increase in transient pressure (compared with tests with a locally restrained bend) for a 60° sharp bend. The constrained-bend tests contradicted with Swaffield (1968)’s findings: The transient pressure lost at the fixed bend was smaller than 1% for all bend angles (30°, 60°, 90°, 120°, and 150°). D. J. Wood is among the pioneers of FSI, and is 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 flow-induced vibrations (FIV) community) “Keswick” conferences. Fahy and Firth (1978) presented a limited amount of measured data for high-frequency excitation that caused pipe ovaling and higher modes of wall vibration. No attempt was made to provide a particular form of ideal structural boundary condition. The authors stated that the presence of bends increases the efficiency with which disturbances (generated by pumps) evolve into resonance of the pipes with beam-type flexure. And they 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. Due to elbow motion, FSI 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 (1 bar=$10^5$ Pa) pulse for 3 ms. The travelling pulse caused plastic deformation in thin-walled nickel pipes. Although the end and elbow flanges were anchored to the ground to limit their motion, some of the incident pulse’s energy was expended in axially expanding the pipe as the pulse hit the blind flange. An effect of the elbow of 18% (on the incident pressure pulse) was indicated—similar to Swaffield (1968)’s findings—and this was attributed to the 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-world systems.

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

**[B5]** The paper by Wiggert et al. (1985) is an excellent introduction to the subject. It is experimentally demonstrated that the "maximum 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 liquid pressure close to the valve was observed owing to a precursor stress wave in the pipe wall that pulled the elbow back (pumping action); the later arrival of the liquid pressure wave pushed the elbow forward (storage action) causing a decrease in pressure.

**[A5]** Tentarelli (1990) carried out five FSI experiments, one of them involving the cantilevered L-tube of Fig. 1c, but with one closed end. The frequency-domain measurement error was analyzed in detail, because this was particularly important near (anti-)resonance conditions. The precision experiments were carried out using tiny tubes.

**[A6]** de Jong (1994, 1995) also used the configuration shown in Fig. 1c, but with heavy masses attached to both ends. The bottom mass behaved as a rigid body; the top mass was intended 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 (1996a, 1996b) 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, initial sagging was an issue.

**[B6]** Tijsseling et al. (1996) presented experimental data on a freely suspended, fully closed L-pipe (Fig. 1d) 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 this L-shaped pipe.

**[A8]** Caillaud et al. (2001) studied the modal behavior of an L-shaped system with an open end (Fig. 1c), where the water level in the vertical leg was varied. Particular attention was paid to the design of the clamped end (because nothing is perfectly rigid), the pressure taps, and the de-aeration of water (by waiting a month before performing a test).

**[B7]** Steens and Pan (2008) used a similar set-up to that used by Tijsseling et al. (1996) (Fig. 1d) but with a pendulum impact hammer that produced a short-duration pulse in both the liquid and the pipe wall.

**[B8]** The experimental facility used by Altstadt et al. (2008) had a closed vertical end hit by an accelerating column of liquid. Unlike Swaffield (1968), 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 loose elbows). The incentive of their study was pipe impact loads and responses due to (steam) condensation-induced waterhammer in (nuclear) power plants.

## 4 Conclusions

Carrying out and documenting laboratory experiments is demanding and time consuming. Large amounts of data have to be analyzed and presented in a compact manner. In general, this is more challenging and expensive than running computer simulations. Published experimental data last for years, and are used by many researchers. Everyone in the scientific community tends to trust published experimental data except the experimenter who actually carried out the measurements. Therefore, experimental data must be treated with care. With computer simulations, the situation might be the opposite: Nobody believes (non-validated) computed results except the person who proudly produced them. This review focused on a specific and (in principle) well-defined type of FSI experiment to see what had been achieved and how well-documented the published data were. It is intended to assist in the selection of measured data for validation purposes and in the set-up of new experiments. It is also intended to remind the reader of valuable laboratory investigations.

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 can be observed. For the single-elbow systems considered herein, one general conclusion that can 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, axial stress waves in the pipe wall—causing precursors traveling ahead of the main pressure wave—may pull the elbow back and create additional pressure as a result of pumping action. The classical Joukowsky pressure is overshot between 6% and 33% due to FSI in the time-domain experiments. Significantly altered resonance frequencies because of elbow vibrations have been observed in all frequency-domain experiments. It is difficult, if not impossible, to find general rules for multi-elbow systems, but reliable FSI theory and corresponding software exist for predictions as accurate as allowed by the input data. The underlying FSI theory has been validated due to the hard work of all the researchers mentioned herein. Their results are still used today as benchmarks in FSI validation studies.

Most waterhammer experiments involve undesirable effects of FSI. In this sense, Holmboe and Rouleau (1967) were right to embed their entire laboratory system in solid concrete, and Mikota et al. (2017) were prudent to use a special arrangement of cubic aluminum blocks with cylindrical bores.

Although the subject has reached a certain level of maturity, future research on FSI and FIV in liquid-filled piping systems will certainly feature more computational fluid dynamics, pipe stress analysis, multi-phase flows, non-elastic non-uniform pipes, improved modeling of supports, and possibly machine learning. Regarding elbows, to calculate local pressure forces accurately in view of fatigue issues, one may combine 3D multi-fluid flow with structural shell models, although FSI might be one-way coupling only if the fluid mixture contains a significant amount of gas.

## Acknowledgment

This review is based on the author's preprint TUE-CASA 16-16.

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## Appendix A

**Table A1 Frequency-domain experiments**

| No. | Reference | $L_1$, $L_2$ (m) | $D$ (mm) | $e$ (mm) | Fluid | Solid | u/d (BC fluid) | u/d (BC solid) | Elbow orientation, type, and restraint | Type and number of intermediate supports | Excitation | Vibration (Hz) | Instr. | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [A1] | Blade et al., 1962 | 10.4, 10.4 | 22.1 | 1.65 | Fuel, JP-4, F-40, avtag | Steel | Open (P)<br>Open, orifice | Fixed<br>Axially free, laterally fixed | Hor. mitre, free $R_c/D\approx1$ | 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] | Davidson and Smith, 1969 | 0.91, 0.91 | 114.3 outer | ? | Oil | Copper-nickel | Closed, piston<br>Open, free surface | "Fixed"<br>Free | Vert. mitre, free | None, cantilever | Piston | Forced 20–2000 | 2 PT, 6 acc. | "Fixed" point moved: see Brown and Tentarelli (1988) (p.148) |
| [A3] | Fahy and Firth, 1978 | 1.1, 1.1 | 60.2 | 1.63 | Water | Steel | Closed, piston<br>Open, special | Clamp<br>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] | Wilkinson, 1978 | 0.25, 0.65 | 70 outer? | 0.9 | Water | ? | Closed?<br>Closed? | Mass<br>Free | Vert. mitre, free 0.14 m long | None? | Shaker | Forced up to 1100 | ? | |
| [A5] | Tentarelli, 1990 | 1.16, 0.64 | 5.1 | 1.25 | Hydr. oil | Steel | Open<br>Closed | 150 kg clamp<br>Free | Vert. 0.15 kg elbow 75 mm long | None | Valve | Forced up to 2000 | 1 PT, 1 acc. | Measured lumped masses and rotary inertia |
| [A6] | de Jong, 1994, 1995 | 1.45, 1.41 | 150 | 4.5 | Water | Steel | Closed<br>Open, free surface | 572 kg mass<br>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] | Svingen, 1996a, 1996b | 8.5, 11.15 | 80 | 1.5 | Water | Steel | Open (P)<br>Open | Rigid<br>Rigid | Vert. elbow 0.2 m long ff=10.7 | None | Rotating valve | Forced up to 300 | 2 PT, 2 acc. | Initial deformation of L-shape due to slenderness, unintentional valve motion (Svingen, 1996a) (p.76) |
| [A8] | Caillaud et al., 2001 | 1.6, 1.5 | 93.3 | 4.2 | Water | Steel | Open<br>Closed | Fixed<br>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; BC: boundary condition; u: upstream or left; d: downstream or right; $D$: pipe inner diameter; DT: displacement transducer; $e$: pipe wall thickness; avtag: airplane fuel; ff: flexibility factor; FM: flow meter; FT: force transducer; Instr.: Instrumentation; hor.: horizontal; hydr.: hydraulic; $L$: pipe length; LDV: laser Doppler vibrometer; P: constant pressure; PT: pressure transducer; $R_c$: radius of bend curvature; SG: strain gauge; Temp.: temperature; vert.: vertical; ?: omission or lack of clarity in reported work

## Appendix B

**Table B1 Time-domain experiments**

| No. | Reference | $L_1$, $L_2$ (m) | $D$ (mm) | $e$ (mm) | Fluid | Solid | u/d (BC fluid) | u/d (BC solid) | Elbow orientation, type, and restraint | Type and number of intermediate supports | Excitation (ms) | Initial flow velocity (m/s) | Instr. | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [B1] | Swaffield, 1968 | 6.7, 5.5 | 38.1–76.2 | 1.6–6.35 | Water | Polythene, steel, copper, aluminum | Open<br>Closed | "Free" elbow<br>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 (Swaffield, 1968), unwanted pipe motion (Wilkinson, 1980) (p.197) |
| [B2] | Wood and Chao, 1971 | 6.1, 6.1 | 12.7 outer | ? | Water? | Copper | Open (P)<br>Closed | Fixed<br>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 by Lavooij and Tijsseling (1989) |
| [B3] | A-Moneim and Chang, 1979 | 1.5, 1.5 | 72.9 | 1.65 | Water | Nickel | Closed<br>Closed | Fixed<br>Fixed | Hor. $D$=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] | Hu and Phillips, 1981 | 1.0, 1.0 | 19.05 outer? | ? | Hydr. oil? | Aluminum | Closed<br>Closed | Fixed?<br>Free? | Welded $R_c/D$=6 | ? | Pellet impact 0.2 | 0 | 1 PT, >8 SG | Static PT? |
| [B5] | Otwell, 1984; Wiggert et al., 1985 | 7.7, 12.3 | 26 | 1.27 | Water | Copper | Open (P)<br>Closed | Fixed<br>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] | Tijsseling et al., 1996; Tijsseling and Vaugrante, 2001 | 4.51, 1.34 | 52 | 3.9 | Water | Steel | Closed<br>Closed | Free<br>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 (Tijsseling and Vaugrante, 2001) |
| [B7] | Steens and Pan, 2008 | 1.5, 6.5 | 34.85 | 3.2 | Water | Steel | Closed<br>Closed | Free<br>Free | Hor. $R_c/D$=2.2 | 4 wires | Impact hammer pulse 1–2 | 0 | 2 PT, 4 acc., 1 FT | |
| [B8] | Altstadt et al., 2008 | 1.8 (or 1.0), 1.5 | 207 | 6.0 | Water | Austenitic steel | Open (P)<br>Closed | Fixed<br>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 have been present at the dead end |

The explanations of variables and abbreviations are the same as shown in Table A1

# 中文概要

**题　目：关于单弯管系统中流固耦合实验的概述**

**概　要：**振动的管道中的流固耦合现象来源于作用于松散弯管头上的不平衡压力。这一现象在理论研究和实际工程应用中均引起了广泛的关注。本文回顾了16个实验室所开展的基于充液单弯管（L形管）系统的流固耦合实验。附录A和B分别概述了八个频域实验和八个时域实验。几乎所有的实验都旨在研究充液管道系统中的流固耦合作用以及移动弯头对系统动力学行为的影响。本文的历史回顾对表征流固耦合作用的实验具有指导意义。

**关键词：**流固耦合；实验室实验；肘形弯管；肘管弯头；弹性流体