Practical Guidelines for fluid-structure interaction in pipelines: A review.

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Fluid-structure interaction (FSI) exists in liquid-carrying pipes when pressure waves in the liquid cause pipe loads, strains and displacements (and vice versa). FSI has been responsible for many pipe and machinery failures, causing loss of containment, environmental damage, fire and even loss of life. The problem is complex and not well understood by many pipe-work designers, constructors and operators. Currently there are no standards and few guidelines to assist in determining which systems might be at risk. The costs of available methods of analysis are such that they are reserved for only the most obviously high-risk cases. This paper reviews existing guidelines and practices related to fluid-structure interaction in pipelines. It is intended to provide a basis for further work on the development of practical guidelines and to illustrate the essential need for this work.

1. INTRODUCTION

Currently, most analyses of FSI in liquid-filled pipe systems comprise two separate analyses undertaken sequentially. Typically, a fluid-transients code is used to determine pressures and flow velocities, which are then used as input to a structural dynamics code. This so called uncoupled approach is better than no analysis at all, but it has severe limitations because it neglects crucial interactions between the liquid and the pipe.

Pressure pulsations and mechanical vibrations in liquid-transporting pipe systems affect performance and safety. Bad performance costs money; accidents can cost lives and cause severe environmental damage. Symptoms include vibrations, noise and fatigue damage to piping, supports and machinery. Other disruptions include leaking flanges, burst rupture disks, relief valve discharges and pipes jumping off their supports.

There is a pressing need for identifying the 98% of systems where FSI is not a major issue so that attention can focus on the few where analysis is truly merited. The need to find “a definition as to when FSI needs to be considered” was noted in the opening address at the 6th Pressure Surges conference, 1989 (by E. B. Wylie). Before beginning the development of practical guidelines for fluid-structure interaction in pipe systems, the first step must be to determine what already exists. How detailed are existing guidelines, standards, ground rules, etc? What do they describe? Do existing guidelines with respect to other behaviour mention FSI? Thus, this paper reviews a number of existing guidelines. This is by no means a complete...

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list of standards, but the aim is to highlight some of the more important and well-known titles. Also included in this review is a section reviewing other published work related to the task of providing practical guidelines. A final section gives an overview of pipeline safety, with developments in the regulations (in the US) as recently as 14th March 2001. These developments have been prompted by a number of accidents.

2. **FSI PHENOMENA**

Waterhammer analyses provide information on the liquid behaviour in a pipe system, e.g. pressures. Structural dynamics provides information on the pipe system, e.g. stresses, reaction forces. In conventional waterhammer analyses, the propagation speed of the pressure waves includes the pipe elasticity, but pipe inertia and pipe motion are neglected. This is acceptable for rigidly anchored pipe systems (e.g. buried pipes, but not in case of earthquakes). However, pipe motion affects dynamic pressures so that for less restrained systems the two analyses cannot properly be considered independently. Interaction (two-way) between the liquid and the structure is termed FSI. When compared to conventional analyses, predictions including FSI may lead to higher or lower extreme pressures and stresses, changes in natural frequencies and more damping and dispersion in the pressure and stress histories.

Investigating FSI events, there are a number of factors that must be considered. Attention may focus either on the sources of excitation or on possible responses to an excitation. The types of excitation are categorised into either a single large event or repetitive excitation. Three types of liquid-pipe coupling can be distinguished: friction, Poisson and junction coupling. Friction and Poisson coupling act along the entire pipe (distributed forces). Junction coupling acts at specific points (local forces) such as junctions or discontinuities in the pipe network (i.e. bends, valves). Poisson coupling relates pressures in the liquid to axial stresses in the pipe through radial contraction/expansion and leads to precursor waves. Junction coupling is usually more significant than Poisson coupling; exceptions to this would be in systems that are very highly constrained (e.g. underground). Friction coupling is the interaction between the pipe wall and the fluid. It has the smallest effect on the overall response and is most often neglected.

3. **ANECDOCTAL NEED FOR GUIDELINES**

An FSI Advisory Group meets biannually in Dundee. Its aim is to provide guidance for the direction of research at Dundee and includes members from both academia and industry. Fifteen people from a wide range of backgrounds attended the meeting. The first item of its meeting on 11th April 2000 for the FSI Advisory Group was a discussion session on existing guidelines. Each participant was asked to contribute any knowledge of the existence of standards, guidelines, and ground rules, etc concerning FSI. Discussion on the subject at this, and previous meetings, has highlighted a growing interest and brought forward many points that need to be considered. There appears to be relatively little literature on the subject, but a few standards and related articles are discussed in later sections.

Foremost in the discussion was an EU project [6]. Part of this project investigated available standards, codes and rules of fluid dynamics (transients) in pipeline systems, FSI, and leak detection methods. More details are given in section 4.

It was agreed that FSI is normally of low importance for water sewage systems and buried pipes.
Possible methods for assessing FSI in systems were discussed. Two approaches were suggested, namely focussing either on sources of excitation or on responses to excitation. Both are important, but it is sometimes inevitable that only one can be considered reliably. The first approach relies on identifying all possible sources of excitation (e.g. pump trip, valve slam, periodic excitation from rotating machinery) and minimising them. When this approach is not deemed sufficient, FSI analysis is required and attention needs to focus on likely problem areas (e.g. T-pieces, valves, bends, rigid supports).

It was agreed that anchor forces are a big issue. In the design of anchors, the problem of dynamic loads has to be dealt with. There are lots of examples of failures of supports and anchors.

Measured data plus complete descriptions of the test systems are needed to be able to simulate experiments numerically. Most FSI measurements have been obtained under laboratory conditions; field measurements are needed.

4. EXISTING GUIDELINES AND STANDARDS

There now follows a review of some of the better-known standards, including those in which FSI is mentioned.


This standard provides general requirements for the assessment of piping system vibration in nuclear power plants. It includes steady state and transient vibration testing and acceptance criteria. The standard classifies piping systems and defines an acceptable peak velocity and peak displacement. These criteria are based on a correlation between the maximum peak deflection and the maximum flexural stress of a piping span at the first natural mode. The expressions for these criteria are given in terms of a number of correction factors.

Baratte et al. [2] examine the ASME code. They give a number of example subsystems with various end conditions and provide a method of evaluating, for any pipe system, the corresponding values of the correction factors. Correction factors have been calculated for piping systems not covered by the standard and also for modes other than the first.

Comment: The standard is limited to specific layouts, although these are extended by [2]. Most importantly in [2] is the subdividing of a complex piping system into elementary subsystems. It provides a simplified method for assessing vibrations, not how to predict possible vibrations or the influence of FSI.

Dutch Standard NEN 3650: Requirements for steel pipeline transportation systems. [9,10]

This standard provides criteria for a simplified analysis procedure. When designing a transport pipeline system, it is necessary to quantify the loads to which the system may be subject. It states that pressure waves, which shall be included in the analysis, are found in one of three ways (in ascending order of applicability and predictive value/accuracy): the Joukowsky formula, classical waterhammer analysis or waterhammer with FSI. Joukowsky's equation is reported to be a quick method of calculating the maximum pressure rise generated by the relatively rapid closure of a valve at the end of a pipeline, but to be unsuitable for analysing the effects of pump shutdown and "slow"-closing valves. Also it is unsuitable if the waves are likely to be
reflected and it can then give values too high or too low. Water-hammer calculations are said to provide a more accurate picture and to analyse rigidly anchored pipeline systems reasonably well. If the pipeline has freedom of movement, particularly above-ground pipelines, predictions can be substantially different. Finally FSI analysis is described as the most accurate, though not in detail, giving reference to two journal papers for further information.

Comment: No further guidance is given on which method of analysis should be used in practice.

German guideline: DVGW W303. Dynamische Druckänderungen in Wasserversorgungsanlagen (Dynamic pressure changes in water supply installations) (in German) [4]

This guideline provides a detailed description on pressure transients and how to deal with them in the design stage of pipe systems. The physical basis of the problem, with simple examples, is given, including the use of the Joukowsky equation, but the guideline warns that classical methods are meaningful only approximately. It states that the speed of the shock wave is reduced by the elasticity of the pipe material, and is also influenced by other factors, in particular the non-linear behaviour of plastic pipelines.

Section 3.1.4 describes FSI: “Because of the interaction between water and pipeline, dynamic pressure changes lead to non-stationary axial- and radial-movements of the pipe-shell.” (Translation).

Also, it states that interconnected parts (e.g. supports) can have an effect.

The waterhammer equations are given and calculation methods described (e.g. method of characteristics).

Section 4 provides information for planning whilst respecting the causes and possible necessary measures to restrict dynamic pressure changes. The possible causes of dynamic pressure changes and methods to restrict them are described (with appraisal of each method). The possibility of avoidance through elimination of causes is examined, with examples (e.g. through the change of design (see comment)).

Comment: Whilst FSI is mentioned; there is no comment on when it should be considered or how it is calculated. Also, although the possibility of avoidance of transients through the change of design is raised, there is little detail as to how this may be achieved (with the exception of simple examples).


In this standard it is noted that pressure surges in liquid pipelines may be produced by sudden changes in flow and that calculations should be carried out to assess the maximum positive and negative surge pressures in the system.

Comment: No guidance is provided regarding suitable calculation methods.

EU Project: Transient pressures in pressurized conduits for municipal water supply and sewage water transport. [6]

The main objective of this project is to “provide the EU with ground rules for standardising all issues relating to the manufacture, design and construction of water and sewage pipelines, all with specific reference to pressure transients”.

The project is divided into 6 work packages (WP). Of importance to this review are WP1 and WP5.

WP1: Standards and ground rules

This part of the project was an investigation of available standards and ground rules within EU, Australia and USA of fluid dynamics (transients) in pipeline systems, FSI,
and leak detection methods. It showed that in most European countries very little
detail existed. Only the German DVGW code tells us how to apply transients in the
design stage of pipe systems, although both waterhammer and FSI are mentioned in
the Dutch NEN code (see sections examining each code for more details).

**WP5: Collect and analyse fluid-structure data**
The aim of this work package is to collect data with respect to FSI and to assess the
feasibility of test methods (and the capability, accuracy and reliability of measurement
parameters). The purpose of this is to make people aware of possible problems. Also
included in the WP is the evaluation of the results of measurements.

**Comment:** None

**Other Standards and codes**
There are many other codes and standards that have not been examined and it would
take too long to list each in detail – most standards are very long, with many parts, so
that unless guided by experience, it is difficult to identify which part is of significance
for this review. One standard not included is ASME B31: this provides a large amount
of information, including the maximum allowable design pressure.
Also not included in detail include standards from Australia, Canada, Finland, France,
Italy, Japan, Mexico, Norway, Russia, Saudi Arabia, Slovenia and Sweden. The
Appendix, Websites of Interest, provides web addresses for some of the standards
agencies throughout the world. An initial search of standards from these countries has
not found any reference to FSI.

**5. OTHER PUBLISHED WORK**

Most of the literature focuses on the analysis of FSI, not on giving guidelines for its
prevention. The exceptions to this include:

**Lavooij and Tijsseling (1991), [8]**
Lavooij and Tijsseling propose a provisional guideline to judge when FSI is of
importance. Their work relates to a simple one-elbow system with specific end
conditions. They show a relation between time scales for the fluid, the structure and
the excitation, and the occurrence of FSI related events.

**Comment:** Very good piece of analysis, but it is (probably) valid only for the special
case considered.

**ESDU International (1994), [5]**
Criteria are presented to judge when FSI is of importance. They are fairly
general and relate time scales between the fluid, the structure and excitation. The
assessment requires the estimation of three time-scale parameters and is based on a
similar method to that of Lavooij and Tijsseling.

**Comment:** Assumes the relationship between time scales (see Lavooij and Tijsseling)
can be applied more generally. There does not appear to be any definite evidence to
prove that this is justified.

**Hamilton and Taylor (1996), [7]**
Hamilton and Taylor focus on one-off events and on the initiation of events.
They outline a framework, incorporating simple acceptance criteria, for determining
the level of study needed.

**Comment:** Focuses on operating conditions and the recognition of potential problems
(which requires experience). It is a method of assessing a piping system. FSI events
are not the focus of the study and there is no guide for the effect of piping layout.
Pipeline Compressor Research Council and Southwest Research Institute (1994), [12]

This course focused on controlling the effects of pulsation and fluid transients in piping systems (aimed at gas pipelines). Chapter 5 of the course literature, entitled Piping Vibrations, discussed natural frequencies and mode shapes, in particular noting the importance of peak displacement and the point of maximum bending of the mode shapes. It provided some simple design considerations and guidelines.

**Comment:** The course was not directed at FSI.

6. **PIPELINE SAFETY**

This section gives a brief overview of developments within pipeline safety. There appears to be a large amount of interest in this area and a very large amount of information available.

The Office of Pipeline Safety provides statistics on the number of accidents in the United States, together with casualty figures, costs and causes of accidents: Data from 1986-2000 shows there has been a total of 5979 accidents, with 357 deaths and 3494 injuries, costing in excess of $1 billion. Of the causes listed for the accidents, “failed pipe” is one, but with no mention as to the actual cause of failure (outside force is a separate heading); also, “other” accounts for a large number.

There are many codes relating to pipeline safety. In particular of interest are Title 49 USC and CFR [15, 16]. The regulations they describe aim to ensure safety in design, construction, inspection, testing, operation and maintenance of pipeline facilities. Also, they set parameters for the pipeline safety program and even for the implementation of an anti-drug and alcohol misuse programs for operators.

A white paper [11] from 1996 provides a very good overview of pipeline safety, highlighting some of the accidents that have occurred. Pipelines have a worse accident history than tankers and barges (between 1982-92, 240% more petroleum products were spilled from pipelines than tankers and barges), but despite this, tankers spills generally receive much more media attention.

During the 106th Congress there were several acts proposed aimed at improving pipeline safety. Two of these [13,14] were initiated by accidents. The first was initiated following an accident (June 1999) in which two 10 year old boys were killed. It proposed amendments to Title 49 USC [15], including liability and enforcement (and fines), training for operators, inspections and to guide the direction of research. However, despite a unanimous vote in the Senate (7/9/2000, votes: 99-0) this Act failed to be passed in House (10/10/2000, votes: 232-152). Many groups, including those whom had previously supported it, now naming it as too weak, opposed the bill:

"Critics of the stronger House legislation say it has no chance of passing during this Congress, therefore, we must support the weaker Senate version—something is better than nothing. I disagree, once pipeline safety legislation is passed, the urgency to revisit the issue will diminish. At least until another deadly explosion" — extract from debate in House of Representatives (available from Library of Congress)

The second act was initiated following an accident killing 11 people in August 2000. This aimed to authorize a coordinated research program to ensure the integrity, safety and reliability of pipelines. Of particular interest is the proposed research on risk and reliability analysis models, and any other areas necessary to ensure the public safety. Since these acts were proposed a new session of Congress has begun (107th Congress) and in this four more acts have been proposed: two entitled “Pipeline Safety Enhancement Act of 2001” (H.R.459 and S.299) and the other two “Pipeline Safety...
Improvement Act of 2001” (S.141 and S.235). All four propose amendments to Title 49 of USC [15].

Comment: There is no mention in any of the regulations with respect to the possibilities of transients (or FSI).

7. CONCLUSIONS

From the above review, it is clear that there is very little information regarding FSI and when this phenomena needs to be taken into account. Very few standards make reference to pressure transients (with little detail) and, of these, only one mentions FSI (referring to journal papers for those requiring more information). Generally, the standards express the need for pressure surge analysis, but do not give guidance about how detailed this study needs to be. Given the high cost of a fully coupled analysis, a guideline showing when this is/ isn’t required would be of great value.

Acknowledgements

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6. EU Project: Transient Pressures in Pressurized Conduits for Municipal Water and Sewage Transport. (Project managed by the BHR Group Ltd. In association with WL| Delft Hydraulics, TNO Building and Construction, University of Perugia, University of Lisbon, Flowmaster International and University of Newcastle-upon-Tyne)
10. NEN-3650 Requirements for steel pipeline transportation systems. 1998, unofficial translation.

12. Pipeline Compressor Research Council. Pulsation Control in Machinery and Piping. Course held in Aberdeen, 1994 (Short course, conducted in association with Southwest Research Institute)


Websites of Interest

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Office of Pipeline Safety
Library of Congress
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Canadian Standards Association
German Institute for Standardisation
German Association for Gas and Water
International Standards Organisation
Japanese Industrial Standards Committee
Nederlands Normalisatie-instituut
International Library Service
National Resource for Global Standards
National Transportation Safety Board
Saudi Arabian Standards Organization
Standards Council of Canada (SCC)
Direccion General de Normas (DGN Mexican Norms)
Finnish Standards Association
Standards and Industrial Research of Malaysia
Swedish Standards Institute
National Codes and Standards of the Russian Federation
Norwegian Standards Association
Standards Australia (SAA)
Italian Standards Organisation
Standards and Metrology Institute (Slovenia)