FLUID-STRUCTURE INTERACTION IN NON-RIGID PIPELINE SYSTEMS - LARGE SCALE VALIDATION EXPERIMENTS

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ABSTRACT

The fluid-structure interaction computer code FLUSTRIN, developed by DELFT HYDRAULICS, enables the user to determine dynamic fluid pressures, structural stresses and displacements in a liquid-filled pipeline system under transient conditions. As such, the code is a useful tool to process and mechanical engineers in the safe design and operation of pipeline systems in nuclear power plants.

To validate FLUSTRIN, experiments have been performed in a large scale 3D test facility. The test facility consists of a flexible pipeline system which is suspended by wires, bearings and anchors. Pressure surges, which excite the system, are generated by a fast acting shut-off valve. Dynamic pressures, structural displacements and strains (in total 70 signals) have been measured under well determined initial and boundary conditions.

The experiments have been simulated with FLUSTRIN, which solves the acoustic equations using the method of characteristics (fluid) and the finite element method (structure). The agreement between experiments and simulations is shown to be good: frequencies, amplitudes and wave phenomena are well predicted by the numerical simulations. It is demonstrated that an uncoupled water hammer computation would render unreliable and useless results.

NOMENCLATURE

\[\begin{align*}
A_r & = \text{cross-sectional discharge area} \\
\bar{D} & = \text{internal diameter of the pipe} \\
\bar{e} & = \text{pipe wall thickness} \\
G & = \text{shear modulus} \\
H & = \text{fluid pressure head} \\
J & = \text{polar moment of inertia} \\
L & = \text{length} \\
t & = \text{time} \\
u_{x,y} & = \text{axial pipe displacement} \\
\bar{V} & = \text{fluid velocity} \\
x,y & = \text{lateral coordinates} \\
\gamma & = \text{pipe elevation angle} \\
\nu & = \text{Poisson’s ratio} \\
\rho_t & = \text{pipe wall density} \\
A_t & = \text{cross-sectional pipe wall area} \\
E & = \text{Young’s modulus} \\
f & = \text{Darcy Weisbach friction factor} \\
g & = \text{gravitational acceleration} \\
I & = \text{moment of inertia} \\
K & = \text{fluid bulk modulus} \\
P & = \text{fluid pressure} \\
\dot{u}_x & = \text{axial pipe velocity} \\
\dot{V}_r & = \text{relative fluid velocity (} \dot{V}_r = \dot{V} - \dot{u}_x \text{)} \\
\theta & = \text{torsional rotation} \\
\rho_f & = \text{fluid density} \\
\sigma_z & = \text{axial pipe wall stress}
\end{align*}\]

1 INTRODUCTION

Transients in fluid-filled pipeline systems are governed by acoustic waves in the fluid and the pipe
wall. Pressure waves in the fluid, also known as water hammer, interact with axial, bending, shear and torsional stress waves in the pipe wall. The interaction between axial stress waves and fluid pressure waves takes place via radial expansion and contraction of the pipe wall. At junctions (elbows, diameter changes) interactive couplings between all mentioned types of waves may occur.

The FLUSTRAIN (fluid-structure interaction) computer code enables the user to numerically simulate the phenomena mentioned above in serial pipeline systems. The code is based on (extended) water hammer theory (fluid) in combination with beam theories (structure). The beam theory which has been used in this study is the Bernoulli-Euler theory. All relevant interaction mechanisms [2] are implemented in the computer code.

The fluid equations are solved using the method of characteristics (MOC) with an analytical time integration scheme. The structural equations are solved by the finite element method (FEM) with a direct time integration scheme. During each computational time step an iteration process takes care of the fluid-structure interaction.

To validate the computer code, experiments have been performed by DELFT HYDRAULICS in a large scale 3D test facility, allowing axial, flexural and torsional motion. The experiments have been simulated with the computer code and the results are compared and interpreted.

2 BASIC EQUATIONS

2.1 Assumptions

For modelling the fluid behaviour the classical water hammer theory is adopted [3]. The pipe is assumed to be thin-walled and elastic. Radial inertia of the pipe wall is neglected. The local coordinate system is given in figure 1.

2.2 Fluid Equations

The fluid behaviour is described by extended equations of momentum and mass conservation:

\[
\frac{\partial V}{\partial t} + g \frac{\partial H}{\partial z} + \frac{f}{2D} \frac{\partial V}{\partial t} = 0 \quad ; \quad \frac{1}{c_f^2} \frac{\partial H}{\partial t} + \frac{1}{g} \frac{\partial V}{\partial z} - \frac{2\nu}{gE} \frac{\partial \sigma_z}{\partial t} = 0
\]

(1),(2)

The pressure wave speed \(c_f\) is defined as:

\[
c_f = \sqrt{\frac{\nu}{\rho_f (\frac{1}{K} + D / E e)}}
\]

(3)

2.3 Structural Equations

Axial Motion: The axial motion of a straight elastic pipe is described by:

\[
\rho_i A_i \frac{\partial^2 u_z}{\partial t^2} - EA_i \frac{\partial^2 u_z}{\partial z^2} = vDA_i \frac{\partial P}{\partial z} + \rho_f A_f f \frac{\partial V}{\partial t} \frac{\partial \sigma_z}{\partial t} + \rho_i A_i g \sin \gamma
\]

(4)

Lateral Motion: For describing the lateral motion the Bernoulli-Euler theory is applied. The equations of motion in the two lateral directions \(x\) and \(y\) are:

\[
(\rho_i A_i + \rho_f A_f) \frac{\partial^2 u_x}{\partial t^2} + EI \frac{\partial^4 u_x}{\partial z^4} = -(\rho_i A_i + \rho_f A_f) g \cos \gamma
\]

(5)

\[
(\rho_i A_i + \rho_f A_f) \frac{\partial^2 u_y}{\partial t^2} + EI \frac{\partial^4 u_y}{\partial z^4} = 0
\]

(6)

Torsional Motion: The equation of motion is given by:

\[
\rho_f \frac{\partial^2 \theta_t}{\partial t^2} - GJ \frac{\partial^2 \sigma_z}{\partial z^2} = 0
\]

(7)
2.4 Interaction

Equations (2) and (4) are coupled via the expansion ($\nu$, $\sigma$, and $P$). This will be referred to as Poisson coupling. Equations (1) and (4) are coupled via the friction ($f$ and $V_p$). This will be referred to as friction coupling. Equations (1), (2), (4), (5) and (6) are coupled at elbows, diameter changes and other pipe extremities via the local fluid pressure forces (acting as loads at the junctions) and the structural motion of the extremities (influencing the continuity relations of the junctions). This is referred to as junction coupling. For flexible pipeline systems the junction coupling is mostly the predominant type of coupling.

3 SOLUTION PROCEDURE

In this procedure the water hammer equations (1) and (2) are solved by the MOC. The structural equations (4), (5), (6) and (7) are solved by the FEM with 12 degree-of-freedom beam elements. Both methods are standard in their field of application. The fluid pressures from the water hammer computation are taken into account as distributed and concentrated loads in the structural dynamics computation. In its turn the computed motion of the structure influences the distributed (Poisson effect) and concentrated (junction effect) storage terms in the water hammer computation. This coupling is taken care of by an iteration process during each time step.

A Rayleigh damping matrix can be activated in the solution procedure. In the presented material the damping has been set to zero. The Newmark $\beta = \frac{1}{4}$ time integration scheme is applied.

4 EXPERIMENTS

The experimental set-up is given in figure 2. It consists of a water-filled closed loop with a variable speed pump, an air vessel, 77.5 m of welded pipe, six elbows (square bends), a fast acting shut off valve and a control valve. A flexible hose closes the loop between the control valve and the pump.

The structural boundary conditions of the system are:
- Rigid supports at locations A and H
- Bend supports at locations B and G, allowing axial motion and torsional rotation
- Suspension wires at about every 6 m along the pipe
- Adjustable spring at location E, in $X_1$ or the $X_3$ direction

Transients are generated by closing the fast acting shut off valve starting from a steady state flow condition. Different initial and boundary conditions are obtained by varying the initial flow rate, the closure time, the stiffness and direction of the adjustable spring. In each experiment, the following signals were measured:
- The steady state flow rate
- 6 dynamic fluid pressures
- 3 forces in suspension wires
- The valve disc position
- 2 steady state fluid pressures
- 9 structural displacements
- 48 pipe wall strains

The signals were recorded simultaneously with a sample rate of 800 Hz during 5 seconds.
5 NUMERICAL RESULTS

5.1 Wave phenomena

Fig. 3. Measured and computed pressure at the shut off valve

In figure 3 the measured and computed pressure-time behaviour at the shut off valve is plotted. The wave speed is 1257 m/s according to equation (3) with \( \rho_f = 998.2 \text{ kg/m}^3 \), \( K = 2.19 \text{ GPa} \), \( D = 108.7 \text{ mm} \), \( e = 3.07 \text{ mm} \) and \( E = 200 \text{ GPa} \) substituted. The initial fluid velocity is 0.3 m/s. At 20 ms the valve is completely closed. In the computed results the pressure change equals the classical Joukowski pressure change \( \Delta P = \rho_f c_f \Delta V = 998.2 \times 1257 \times 0.3 = 3.76 \text{ bar} \).

In the measured signal the pressure drops just before valve closure. This is attributed to an axial displacement caused by the closing motion of the valve and an example of structurally induced fluid-structure interaction.

In the simulations the rigid and bend supports are assumed to be ideal, although in reality they allow some structural motion. For this reason FSI effects appear more prominently in the measured signal during the time interval between 20 ms and 40 ms.

In figure 4 the pressure and stress waves are plotted in a space-time diagram. At 20 ms the valve is fully closed and the basic water hammer wave starts travelling from the valve through the pipe towards elbow G, where it arrives 3/1257 s later \( (t = 22.4 \text{ ms}) \). Here the first FSI junction coupling takes place: the fluid pressure sets elbow G into motion in the (global) \( X_3 \)-direction, thus causing a pipe stress wave in pipe GH, travelling with a speed of 5000 m/s. This wave arrives 3/5000 s later at the valve \( (t = 23 \text{ ms}) \). The effect of this wave is visible in figure 3 as a minor computed pressure rise. The motion of elbow G is relatively small.

The basic water hammer wave arrives 7.5/1257 s after valve closure at elbow F. Via FSI junction coupling the pressure causes two stress waves which propagate towards elbows E and G. The vertical motions are limited because of the rather short length of pipe FG and the bend support at elbow G. Therefore elbow F starts to move mainly in the (global) \( X_3 \)-direction. The tensile pipe stress wave towards elbow E, shown in figure 4, arrives at elbow E 23.5/5000 s later \( (t = 30.7 \text{ ms}) \). Elbow E will then be set into motion and via FSI junction coupling water hammer waves will be generated. These pressure waves propagate into the directions towards elbows D and F. The latter pressure wave arrives 31/1257 s later at the valve \( (t = 55.3 \text{ ms}) \). This indicated in figure 4 by an arrow.

The frequency with a period of about 10 ms, most clearly visible in the time interval between 50 ms and 80 ms, is caused by the stress wave travelling up-and-down through pipe EF.

The computer code appears to be able to simulate the pressure and stress wave phenomena in the pipeline system quite well.
5.2 Pressures

The measured and two computed pressure-time histories at the valve are given in figure 5. The two computed lines are obtained with FSI (the FLUSTRIN computation) and without FSI (the classical water hammer computation). In the measured and FSI computed signals a basic frequency with a period of about 0.2 s is present, whereas in the computation without FSI the basic water hammer period is about 0.25 s \((4L/c_f = 4 \times 77.5/1257)\). This virtual increase in wave speed is also observed by others \([1]\) and is attributed to junction coupling. At each elbow the energy in the water hammer wave is partly transformed into stress wave energy and vice versa, thus redistributing and "smearing out" the waves.

5.3 Displacements

In figure 6 dynamic displacements (relative to the steady state values) in the global \(X_P\)-direction of elbow D are given. The results of the classical computation are obtained by calculating the structural response on the water hammer pressures (without FSI) applied as a time and space dependent load.

The measured and FSI signals agree quite well: amplitudes and frequencies differ not too much. The same basic frequency with a period of 0.2 s as in the fluid pressures is recognizable in the displacements.

Without FSI, the amplitudes are over-predicted significantly by the computation. The basic frequency with a period of 0.25 s of the classical water hammer wave can be recognized.

5.4 Strains

The measured and computed time-histories of a representative hoop strain are presented in figure 7. The agreement between the experiment and the FSI computation is excellent. Amplitudes and frequencies coincide very well. The basic frequency with a period of 0.2 s is visible in both signals.

The classical solution differs substantially from the other two. The basic period of 0.25 s from the classical water hammer theory is visible. The amplitudes exceed the measured and FSI values by 40% (negative) to 80% (positive).

The difference in the absolute maxima is 35% leading to proportionally too large safety margin.
Measured and computed time-histories of a representative shear or torsional strain are given in figure 8. In the measured and the FSI results again close agreement is obtained. Next to the basic water hammer frequency, a structural vibration with a period between 1.2 s and 1.4 s is visible in both signals.

The non-FSI solution overshoots the other two signals by 45%, leading to an even more too large safety margin.

Fig. 8. Measured and computed shear or torsional strain 1.5 m at shut off valve

6 CONCLUSIONS

Pressure surge experiments have been carried out on a flexible water-filled pipeline system in which fluid pressures, structural displacements and strains have been measured. The measured data have been simulated using the FLUSTRIN computer code in which several fluid-structure interaction (FSI) mechanisms are taken into account and also with a more classical approach in which FSI is neglected.

It appears that fluid and structural wave phenomena are numerically simulated well. Junction effects play a predominant role in the transient behaviour of the flexible pipeline system. A frequency shift in the basic water hammer signal has been measured and computed. The amplitudes and frequencies of the fluid pressures, the structural displacements and strains as computed taking into account FSI all agree will with the measurements.

The computations without FSI yield too low values for the pressures and too high values for the structural quantities. This may lead to uneconomic design, with an unintended large safety margin.

Taking into account FSI, it appears to be possible to simulate the transient behaviour of a liquid-filled flexible pipeline system significantly more accurate than with a classical water hammer computation followed by a structural dynamics computation.

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6 REFERENCES