Effect of Anchor Conditions on Structural Responses During Fluid Transients in Pipelines

Abdelaziz Ghodhbani(✉), Ezzeddine Haj Taieb, and Mohsen Akrout

Laboratory of Applied Fluid Mechanics, Process Engineering and Environment, Department of Mechanical Engineering, National Engineering School of Sfax, University of Sfax, Sfax, Tunisia
abdelaziz.ghodhbani1@stud.enis.tn,
{ezed.hadj,mohsen.akrout}@enis.rnu.tn

Abstract. This paper deals with the evolution of structural responses accompanying water hammer in quasi-rigid straight pipelines with emphasis on the effect of the support rigidity. The coupled discrete vapour cavity model (DVCM) is used to simulate axial stress and axial displacement of the pipe in presence of column separation. Transient is caused by a fast-downstream valve closure. The method of characteristics (MOC) with wave-speed adjustment scheme is used in calculation. The numerical results obtained for rigid and viscoelastic supports are performed and compared. The cavity collapse involves greater stress peak at the valve with rigid support, but the stress spikes are reduced in case of viscoelastic support. The axial displacement is more important for this last case because of junction coupling effect. The results obtained are assumed to be important in hydraulic engineering.

Keywords: Water hammer · Column separation · Axial vibration · Fluid-structure interaction (FSI) · Poisson coupling

1 Introduction

Pipeline systems especially full-filled liquid pipes are usually subjected to water hammer events that may lead to severe industrial accidents. Consequently, both liquid and structure behaviour should be accurately predicted in order to install safety devices therein. The classical theory of water hammer deals only with the pressure and the velocity of the fluid in the pipeline. In order to accurately predict structural responses during water hammer, engineers need to use appropriate software packages that consider fluid-structure interaction (FSI), such as the four-equation model. Tijsseling (1993) investigated the four-equation model in axial, radial and torsional motion. Ghodhbani and Haj Taïeb (2017) proposed and validated the four-equation friction model which considers unsteady friction coupling. Their model was applied later in prediction of column separation in pipelines by providing the coupled DVCM (Ghodhbani et al. 2019). This latter is more suitable than the classical DVCM although junction coupling mechanism is ignored. Structure responses, such as axial stress, axial velocity and axial displacement of the pipe can be simulated using the coupled DVCM.

M. Kharrat et al. (Eds.): ICAMEM 2019, LNME, pp. 412–419, 2021.
https://doi.org/10.1007/978-3-030-52071-7_56

However, the authors noted that this simulation may be improved by considering support rigidity and axial pipe stiffness.

This paper investigates structural responses of quasi-rigid straight pipelines with presence of column separation. The emphasis is made on the effect of the rigidity of the supports and the axial vibration of the pipe on these structural responses at different localizations along the pipeline.

2 Materials and Methods

The coupled DVCM was proposed by Ghodhbani et al. (2019) in order to give accurate prediction of column separation in quasi-rigid straight pipeline where transient is caused by a fast-downstream valve closure. This model is obtained by incorporating the classical DVCM into the four-equation water hammer model. The emphasis was made on the effect of FSI on pressure at specific localizations in the pipeline. Dynamic coupling was investigated by considering Poisson and friction coupling; junction coupling was ignored by assuming the valve to be fixed. Unsteady friction was considered and tested against steady friction. Moreover, the variable wave-speed (VWS) method was proposed and used to improve the numerical results. The full-MOC with wave-speed adjustment scheme was used in calculation. Four unknowns are calculated at each time step. While cavitation does not occur, the unknowns are the piezometric head H (or the pressure p) and the velocity V for the liquid and the axial stress σ_z and the axial velocity $\dot{u}_z$ for the pipe. When the pressure drops below the vapour pressure of the liquid p_v, then the algorithm switches to the calculation of the upstream discharge Q_u, the downstream discharge Q_d, the axial velocity of the pipe $\dot{u}_z$ and the axial stress σ_z.

In this work, the coupled DVCM is used to predict stress, velocity and displacement for axial direction of a quasi-rigid straight pipe. Transient is caused by a fast-downstream valve closure fixed at the end of the pipe. Two types of anchor conditions are considered: the rigid support and the viscoelastic support. Thus, two types of boundary conditions (BC) at the valve can be described. If the valve is rigidly fixed, then there is no junction coupling and the BC at the valve are modelled by

$$(Q_d)_{z=L} = 0 \text{ and } (\dot{u}_z)_{z=L} = 0 \tag{1}$$

If junction coupling is considered, the axial velocity at the valve is no longer equal to zero and the equation of motion should be used (Tijsseling 1993; Henclick 2018). Obviously, the vibrating downstream valve of mass m is subjected to pressure force, elastic force of the pipe and equivalent stiffness and damping forces generated by the pipe and the support. Tijsseling (1993) gave the equation of motion as

$$m\ddot{u}_z + c\dot{u}_z + ku_z = Ap - A_p\sigma_z \tag{2}$$

with c is the equivalent viscous damping coefficient, k is the stiffness and A and A_p are, respectively, cross sections of the fluid and the pipe. Noting that c and k are in fact equivalent properties of the system composed by the pipeline and the supports. The determination of the damping coefficient of the pipeline can be obtained from the simple oscillator theory as $c = 2\xi A_p\sqrt{E\rho_p}$ (Budny et al. 1991) with ξ is the damping ratio and E and ρ_p are, respectively, the Young's modulus of elasticity and the density of the pipe-wall. The spring-stiffness of a pipeline of a length L is simply obtained by $k = EA_p/L$. Accurate integration of Eq. 2 can be obtained thanks to the Newmark method (Henclick 2018). By taking β = 1/4 in this method, the differentiation with a backward finite-difference scheme allows

$$(\ddot{u}_z)_{t+\Delta t} = \frac{(\dot{u}_z)_{t+\Delta t} - (\dot{u}_z)_t}{\Delta t} \text{ and } (u_z)_{t+\Delta t} = (u_z)_t + \frac{\Delta t}{2}\left[(\dot{u}_z)_{t+\Delta t} + (\dot{u}_z)_t\right] \quad (3)$$

Thus, after incorporating Eq. (4) in Eq. (3), the second BC can be written with respect to the unknowns of the four-equation model

$$-A(p)_{t+\Delta t} + \left(\frac{m}{\Delta t} + c + \frac{k\Delta t}{2}\right)(\dot{u}_z)_{t+\Delta t} + A_p(\sigma_z)_{t+\Delta t} = \left(\frac{m}{\Delta t} - \frac{k\Delta t}{2}\right)(\dot{u}_z)_t - k(u_z)_t \quad (4)$$

3 Results and Discussion

The physical properties of the experiment of Bergant and Simpson (1995) are used. A copper straight 37.23 m long sloping pipeline of 22.1 mm internal diameter and 1.6 mm wall thickness connects two pressurized tanks fulfilled by a demineralized water. The initial velocity of water is equal to 0.3 m/s so that column separation occurs at the valve following water hammer. The above experiment does not indicate whether the pipe supports are rigid or viscoelastic, and unfortunately there are no experimental records for structural responses.

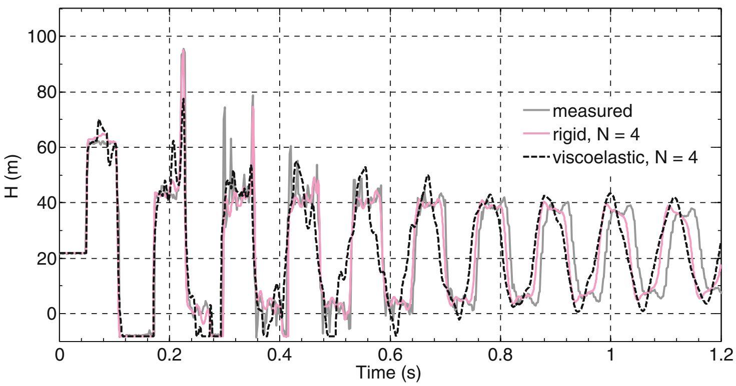

Fig. 1. Piezometric head at the valve

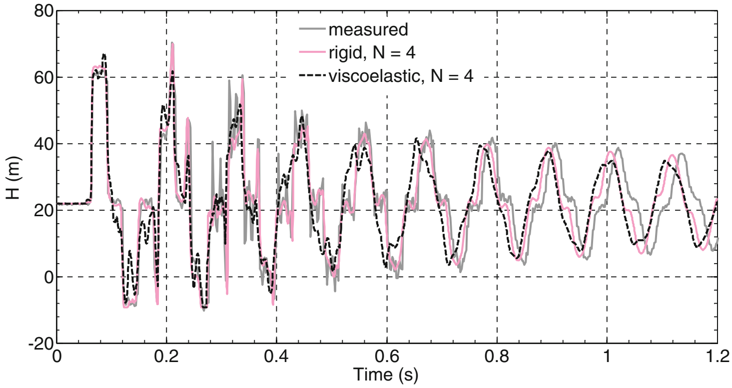

Fig. 2. Piezometric head at the midpoint.

Figures 1 and 2 show the piezometric heads, respectively, at the valve and at the middle of the pipe for a small number of reaches, i.e. $N = 4$ and compare the viscoelastic support to the rigid support. It is observed that the rigid support solution agrees with the experimental result better than the viscoelastic one.

Figure 3 shows the piezometric head at the valve in case of the quasi-rigid support. This latter corresponds to the freely moving valve boundary condition where the equivalent stiffness k is amplified compared to the viscoelastic support, but the equivalent viscous damping c is conserved. It is observed that the quasi-rigid solution

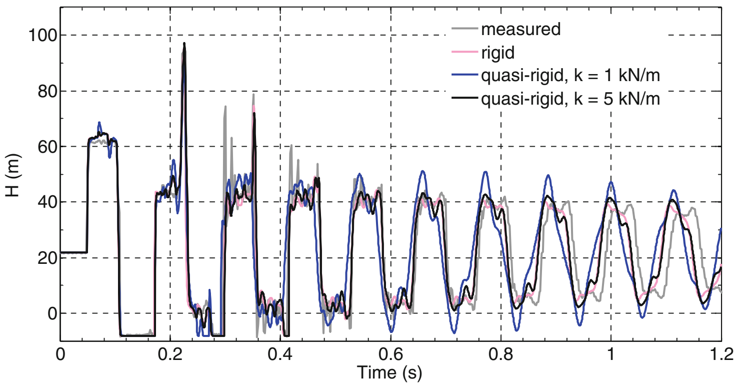

Fig. 3. Piezometric head at the valve and comparison between quasi-rigid and rigid supports.

converges to the rigid solution (fixed valve) when the equivalent stiffness increases. Hence, when the stiffness is so high, the viscous damping effect is no longer observed.

The structural responses at the valve are displayed in Fig. 4 whereas Fig. 5 shows those at the midpoint. The effects of both rigid and viscoelastic supports are simulated and compared. The former corresponds only to Poisson coupling while the latter allows

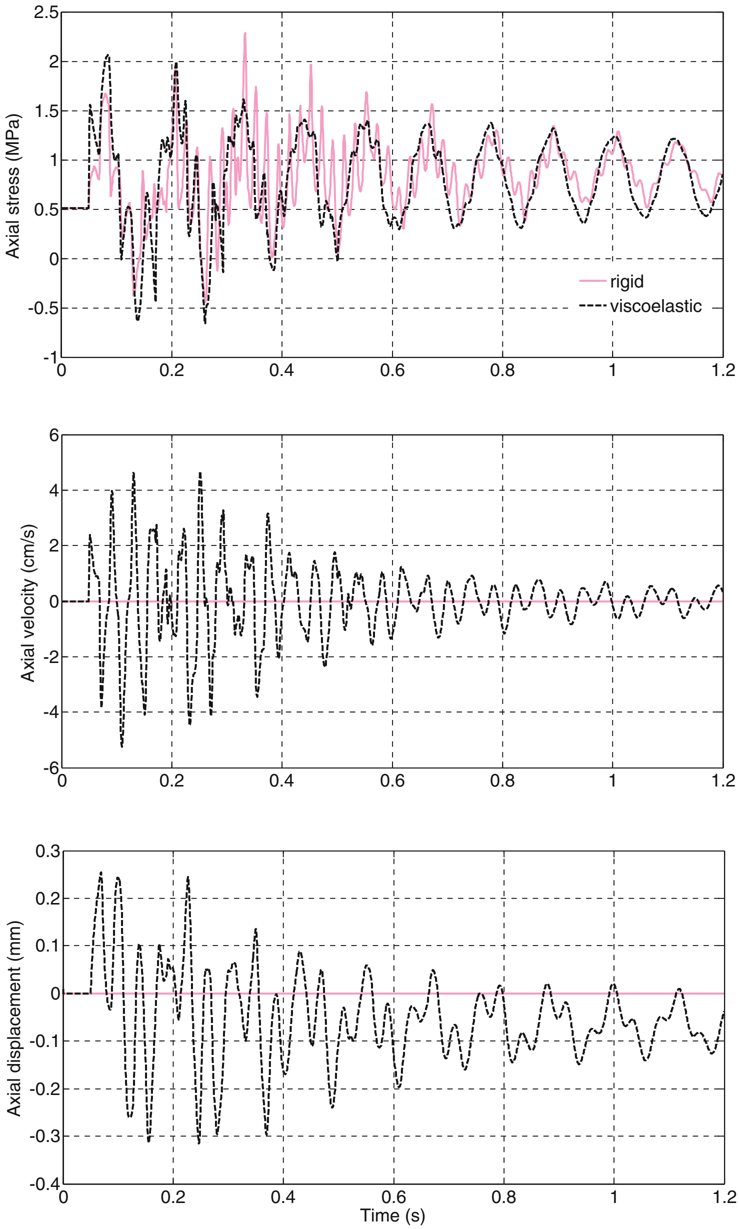

Fig. 4. Structural responses at the valve.

both Poisson and junction coupling. Ghodhbani et al. (2019) provided only axial stress at the valve, which is assumed to be fixed, and they considered that their simulation is of minor spikes since neither support stiffness nor spring-stiffness of the pipe are considered. Heinsbroak and Tijsseling (1994) established that FSI is as important as the

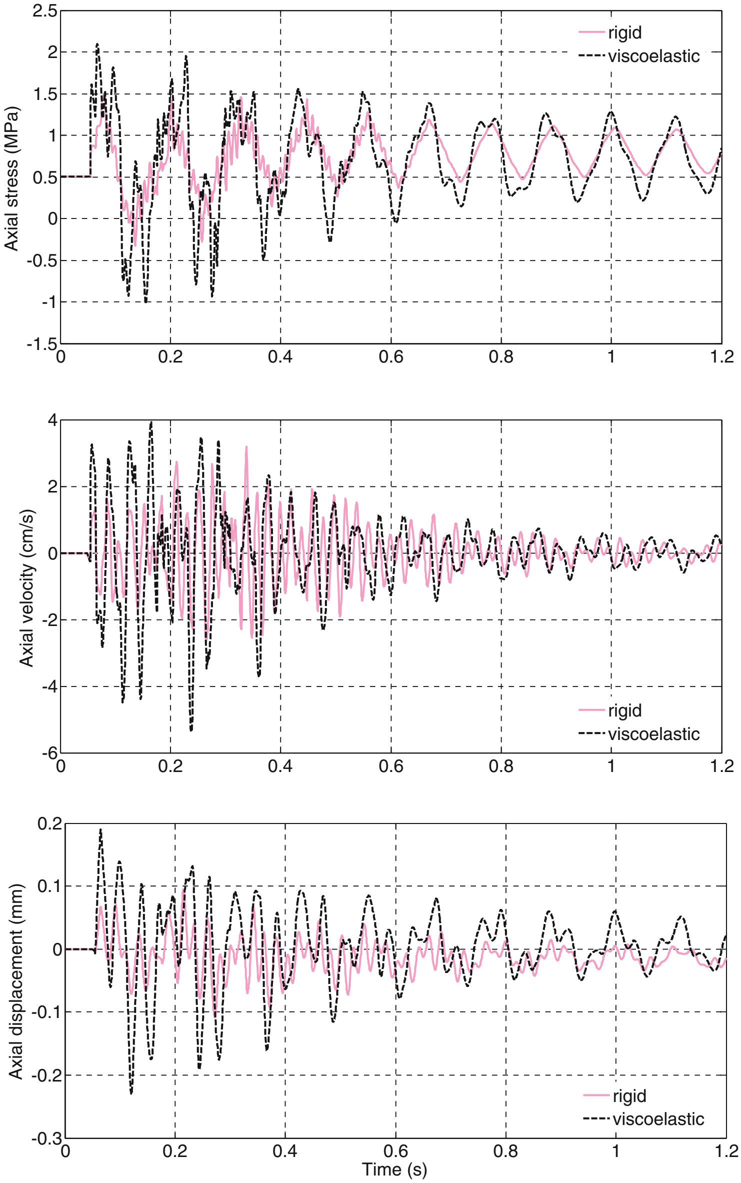

Fig. 5. Structural responses at the midpoint.

ratio of the support stiffness to the spring-stiffness of the pipe is low. If the support stiffness is approximated by 1 kN/m, the above condition is satisfied since the calculated spring-stiffness of the pipe is equal to 361.67 kN/m. Moreover, by taking a damping ratio ξ equal to 5%, the equivalent stiffness of the system formed by the pipe and a unique anchor at the valve can be approximated (Budny et al. 1991). A damping ratio of 2% is assigned to the pipe while 3% corresponds to the anchor which is modelled as linear spring. Due to the short duration pressure pulse following the cavity collapse the stress peak involved by the rigid support at the valve exceeds that of the viscoelastic support (Fig. 1). However, the comparison is inversed at the midpoint (Fig. 2) because of the increased axial. In other word, although the viscoelastic support can lead to more load reduction at the freely moving extremity of the pipe, severe deformation can occur at the midpoint. The accuracy of the predicted structural responses depends on the accuracy of stiffness and damping coefficient introduced in calculation. The correct is the equivalent stiffness and damping coefficient, the accurate is the prediction of the structural responses. Henclick and Maurin (2019) gave and validated an analytical method for the calculation of stiffness matrix of pipeline support.

4 Conclusion

In the paper, the coupled DVCM is applied to simulate structural responses accompanying water hammer with vaporous cavitation in quasi-rigid straight pipelines. The physical properties of the experiment of Bergant and Simpson (1995) is used. The stiffness and damping forces used in boundary conditions are equivalent properties for the pipe and the support together. The calculation was performed for rigid and viscoelastic pipe supports. Poisson coupling corresponds to the former while the latter allows both Poisson and junction coupling. The simulation shows that the cavity collapse at the valve involves axial stress peak greater than that of the viscoelastic support. However, it is observed that junction coupling reduces stress spikes at interior points like the middle of the pipe. Moreover, the viscoelastic support condition involves more displacement in the whole pipe. However, high-frequency responses involved by the rigid support condition are visibly reduced thanks to the viscoelastic consideration.

Further investigation of structural responses can be performed in case of one-elbow pipe system with and without cavitating flow.

Acknowledgments. The authors thank all the members of the Laboratory of Applied Fluid Mechanics, Processes Engineering and Environment of the National Engineering School of Sfax.

References

Bergant, A., Simpson, A.R.: Water Hammer and Column Separation Measurements in an Experimental Apparatus. Adelaide (1995)

Budny, D.D.: The influence of structural damping on internal pressure during a transient pipe flow. ASME J. Fluids Eng. **113**(9), 424–429 (1991)

Ghodhbani, A., Haj Taïeb, E.: A four-equation friction model for water hammer calculation in quasi-rigid pipelines. Int. J. Press. Vessels Piping **151**(3), 54–62 (2017)

Ghodhbani, A., Akrout, M., Haj Taïeb, E.: Coupled approach and calculation of the discrete vapour cavity model. J. Fluids Struct. **91**, 1–21 (2019)

Heinsbroek, A.G.T.J., Tijsseling, A.S.: The influence of support rigidity on water hammer pressures and pipe stresses. In: Proceedings of 2nd International Conference on Water Pipeline Systems, pp. 17–30 (1994)
Henclick, S.: Numerical modeling of water hammer with fluid-structure interaction in a pipeline with viscoelastic supports. J. Fluids Struct. **76**, 469–487 (2018)
Henclick, S., Maurin, A.: Determination of the stiffness matrix of flat springs for modelling of the boundary condition of a pipeline support. Mech. Syst. Sign. Process. **123**, 102–116 (2019)
Tijsseling, A.S.: Fluid-structure interaction in case of water hammer with cavitation, Ph.D Thesis, Delft (1993)