Wall Shear Stress in Pulsating Pipe Flow at Resonance Conditions

Jurij Gregorc¹, Anton Bergant¹, Kamil Urbanowicz³, Arris Tijsseling⁴

¹Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000 Ljubljana, Slovenia
²Litostroj Power d.o.o., Litostrojska 50, 1000 Ljubljana, Slovenia
³Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University of Technology Szczecin, Al Piastów 19, 70-310 Szczecin, Poland
⁴Department of Mathematics and Computer Science, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

jurij.gregorc@fs.uni-lj.si

Abstract. Hydraulic vibrations in liquid-filled pipelines may cause unwanted operational problems. Wall shear stress and consequential damping can reduce the harmful effects of vibrations close to resonance. A large-scale pipeline apparatus at Deltares, Delft, The Netherlands, has been used for pulsating pipe flow tests. The apparatus consists of a constant-head tank, a horizontal 206 mm diameter 49 meters long steel pipe and an oscillating valve at the downstream end. Wall shear stress has been measured by a number of hot-film sensors. Tests have been performed with an average flow Reynolds number of about 22,000. Results of a hydraulic resonance case with oscillating frequency \( f_\text{ex} = 5 \) Hz are presented. Pipe wall vibrations for this case are small. The shape of the velocity profile at resonance conditions is a typical unsteady-state velocity profile with reverse flow near the pipe wall. The CFD study in an axisymmetric domain was conducted to better understand the pulsating flow phenomena. Different settings of boundary conditions, based on the experimental investigations, were used. The CFD results show the unsteady character of wall shear stress at resonance. This phenomenon has not been observed in the measured results to such an extent. The measured shear stress resembles quasi-steady behaviour.

1. Introduction
Prediction of extreme pressure pulsations is an important task in the design process of hydraulic piping system (hydropower, water supply). Operation of the system at resonance conditions leads to amplified pressure oscillations [1]. This paper presents and discusses results for pulsating pipe flow conditions [2], [3], [4]. In essence the pulsating pipe flow is composed of a non-zero mean flow component and a periodic flow component. This type of flow is classified according to the bulk flow Reynolds number, and amplitude and frequency of oscillation. Experimental data for the validation of theoretical models of pulsating flow at resonance conditions in industrial-scale piping systems are not readily available [5]. A large-scale pipeline apparatus at Deltares, Delft, The Netherlands, has been used for pulsating pipe flow experiments. The apparatus consists of a constant head tank, a horizontal 206 mm diameter 49 m long steel pipe and an oscillating valve at the downstream end. The forced frequency of oscillation varied...
between 1.5 and 100 Hz. Results from a hydraulic resonance case with oscillating frequency $f_{ex} = 5$ Hz are presented and discussed in this paper. Pipe wall vibrations and their effects on velocity flow profiles are negligible for this case. Numerical analysis in this paper presents results from CFD simulations in an axisymmetric pipe flow domain. The CFD model [6] gives a detailed picture of the pipe flow structure and helps to explain experimental results close to the wall.

2. Experimental investigation
A layout of experimental system and measuring locations is presented in Figure 1. A more detailed description of industrial-scale pipeline apparatus can be found in our previous publications ([7], [8], [9]).

Two computers were used for data acquisition; one for PIV images and one for the remaining signals. The sampling frequency for each continuously measured quantity (except PIV) was $f_s = 1,000$ Hz. The high-speed PIV camera was set to record at a lower frequency of $f_s = 125$ Hz to accommodate measured data for a time period of 10 seconds. Hydrogen bubbles were used for seeding. DaVis 8.0 special software was used for PIV measurements. The wall shear-stress was measured at three equidistant circumferential positions by Dantec Dynamics hot-film sensors at two different axial locations. One location was at the PIV box ($r_{ex,PIV}$) and the other was 1.15 m upstream. The hot-film sensors were calibrated against shear-stress values calculated from flow-rate and pressure-gradient measurements in steady flows [10].

Even though a large variety of conditions were tested during experimental campaign, here we only focus on one case (Re~22,000; $f_{ex}$=5 Hz) due to the space restrictions.

3. Numerical investigation
An open-source 3D-CFD code OpenFOAM (ver. 6.0) was used to solve the governing equations. The computational set-up consisted of an axisymmetric domain. The flow was considered to be incompressible, transient, isothermal and single-phase. The walls were assumed to be completely rigid. The turbulence aspect of the flow was captured using URANS SST (Shear Stress Transport) $k$-$\omega$ model [11]. According to our previous work [9] it offers satisfactory results.

The geometry was approximated as a 2D-axisymmetric model that measures 0.103 m in the radial and 12 m in the axial direction. The geometric model was discretized to “base mesh” using a block-structured mesh of predominantly quadrilateral cells. In the axial direction ($x$-coordinate) the grid spacings were uniform and equal to $\Delta x = 0.004$ m. In the radial direction, the mesh was created from two blocks. The near wall block ranging from $0.098 < r < 0.103$ m (corresponding to approx. $y^+ = 30$) was divided into 20 cells using simple grading with factor 0.3. The inner block was divided in 46 spacings using simple grading to ensure smooth transition from one block to another. The resulting
“base mesh” has 195000 hexahedral cells and 3000 prism cells along the axi-symmetry. The wall cell size in radial direction is $1.28 \cdot 10^{-4}$ m.

The boundary conditions were as follows: at the inlet uniform velocity was set as a function of time i.e. $u(x, r, t) = u_x(0, r, t) = u_{x, ave} + u_{x, amp} \cos(2 f_x t)$ and $v(x, r, t) = v_r(0, r, t) = 0$. The inlet boundary condition was defined using groovyBC functionality. At the outlet, the gauge pressure was set to 0 Pa. Each simulation was started with the fully developed flow at the maximum velocity, that was obtained with a separate simulation using the steady-state solver. To set adequate inlet boundary conditions the mean velocity and its amplitude were extracted from the experimental case.

The working fluid was water (density $\rho = 998$ kg/m$^3$, kinematic viscosity $\nu = 1e^{-6}$ m$^2$/s). The equations were solved using pisoFoam solver. Temporal discretization was done using the Euler scheme with a fixed time step size $\Delta t = 2e^{-4}$ s. For gradients Gauss linear scheme was used; for divergence Gauss linear scheme was used for all variables except for the velocity, where Gauss linear-upwind scheme was used. Interpolations were performed using linear scheme. The convergence of numerical simulation was checked within every time step using $1e^{-6}$ as a tolerance value or 0.01 as relative tolerance (whichever occurs first).

Simulation ran for 8 oscillations to allow for initial transients to fade out. The CFD runs have been performed on super servers (24 core and 16 core) at the Faculty of Mechanical Engineering, University of Ljubljana.

A mesh independency study was carried out using 2x and 4x refined “base mesh”. Using obtained results, simplified Richardson extrapolation was performed. The relative error for all three meshes were well below 1%. Additionally, we also compared the $u_r$ velocity distribution in radial direction at particular time (when axial velocity on symmetry axis is the smallest) within one oscillation cycle and value of axial velocity in a point over time. The comparison showed that even in case of “base mesh” the results are mesh independent.

4. Results and discussion

4.1. Velocity profiles

One of the main features of oscillating turbulent flow is occurrence of the back flow in the near wall region. This phenomenon can be observed only in small temporal window during single oscillation. Hence, it has been chosen as a validation criterion. In case of numerical simulation, the last simulated oscillation has been chosen for comparison. For the experimental data, one oscillation has been randomly selected from entire data set. The temporal alignment between simulated and experimental data was achieved by comparing temporal variations of axial velocity on axi-symmetry for numerical simulation and in pipe centre for the case of experiment. Data for comparison is taken at $x = 11$ m in numerical simulation and at PIV box in case of experiment. Figure 2 shows velocity profiles at different time instances within single oscillation. Backflow in the near wall region can be seen with both, numerical simulation and experimental data. However, in case of the later the back flow is far smaller. The estimated spatial resolution of the PIV measurements is approx. 2.7 mm, which is more than 2.1 mm thick layer at the wall that typically (according to our current and previous numerical studies) experiences back flow. Hence, it is very unlikely to be able to detect the backflow even if it is there. The velocity profile in case of experiments are clearly showing unsteady and instantaneous character whereas in case of numerical simulation the profiles are smoother, more “RANS like”. Comparing profiles over entire pipe radius, agreement between numerical simulation and experimental data is acceptable.
4.2. Shear stress

As previously stated the wall shear stress was measured using hot film sensors mounted at the pipe wall at three equidistant circumferential positions (Hf2 – 6 o’clock position, Hf7 – 2 o’clock position, Hf9 – 10 o’clock position, all looking in streamwise direction) near the PIV box. Temporal variations of measured wall shear stress for 1 second time period are presented in Figure 3 (bottom graph). The top graph shows predicted wall shear stress by numerical simulation. Please note that temporal alignment in this case is not possible as acquisition systems for PIV and rest of measurements were not synchronized.

Comparison of presented data reveals consistent oscillations according to imposed oscillation frequency as well as similar amplitude of wall shear stress. The most noticeable difference is the fact
that experimental wall shear stress values are always positive (expected according to measurement principle of hot film sensor). In reality, on the other hand, wall shear stress should change the sign in case of back flow near the wall. In this sense numerical simulation presents more sound results. As for experimental data, different factors may affect the measurements: e.g. flush/non-flush mount on the wall, spatial averaging, calibration of hot-film in steady state flow, etc. Further investigation is planned to fully understand the behaviour of hot film sensors when velocity in the near wall region is changing direction.

The results of numerical simulation can be further utilized to investigate relationship between wall shear stress and velocity. A comparison of axial velocity \((x = 11 \text{ m}; \frac{r}{R} = 0 \text{ (acc. to Figure 2)})\) and wall shear stress \((x = 11 \text{ m}; \frac{r}{R} = 1)\) variations with respect to time for single oscillation is presented in Figure 4. There is a clearly visible temporal shift of approximately \(0.1 t_0\) between axial velocity and wall shear stress.

![Figure 4. Temporal variation of wall shear stress and axial velocity within a single oscillation.](image)

The question that naturally follows is how the velocity profiles and shear stress profiles change with time. Following classical fluid dynamics, the shear stress has a turbulent and laminar term that can be calculated with velocity gradient, turbulent and molecular viscosity (see Eq 1).

\[
\tau = \tau_{\text{lum}} + \tau_{\text{turb}} = \mu \frac{d\dot{u}_x}{dy} + \mu_t \frac{d\ddot{u}_x}{dy}
\]

(1)

From simulation standpoint all the necessary data is available. The velocity gradient and turbulent viscosity are changing with distance to the wall. Hence, one can obtain the shear stress profiles across the domain. The values of wall shear stress obtained by this method are presented in Figure 4 with star symbol. It can be seen that they differ from black square symbols that represent wall shear stress as was extracted from numerical simulation. The same procedure was performed on steady state numerical data and gave a less than 3% difference in wall shear stress values. It is clear that in case of oscillating flow there should be an additional contribution to the wall shear stress. This mechanism is currently not fully understood and is subject of ongoing investigation.

5. Conclusions

Pulsating pipe flow tests have been performed with average Reynolds number close to 22,000 and oscillating frequency of \(f_{ex} = 5 \text{ Hz}\). At this frequency, the liquid system’s natural frequency was met,
hence, the system went into resonance indicated by strong amplification of pulsating quantities. Pipe wall vibrations and their effects on velocity flow profiles for this case were small.

CFD simulations have been performed to deepen the understanding of flow phenomena that have been observed by PIV measurements. The shape of the velocity profile at resonance conditions is a typical unsteady-state velocity profile including reverse flow and forward flow excursions near the pipe wall. The SST k-ε turbulence model within OpenFOAM successfully replicated the occurrence of the reverse flow in the wall region. The measured wall shear stress has similar amplitude to wall shear stress obtained by CFD simulation. As the measured wall shear stress is always positive, even in the presence of back flow in the near wall region, further work needs to be done to fully understand how to correlate measured and simulated data for wall shear stress. Based on numerical results the temporal profile of axial velocity and wall shear stress was performed. Results show temporal shift in peak values of 0.1f₀. Additional work is needed to fully understand the discrepancy in wall shear stress as was extracted directly from OpenFOAM and values calculated from typical expression for shear stress.

Acknowledgements

The project Unsteady friction in pipes and ducts carried out at Deltares, Delft, The Netherlands, was partially funded through EC-HYDRALAB III Contract 022441 (R113) by the European Union and their support is gratefully acknowledged. In addition, the authors gratefully acknowledge the support of the Slovenian Research Agency (ARRS) conducted through the program P2-0162 Transient two-phase flows.

6. References

[1] Dörlfler P, Sick M and Coutu A 2013 Flow-induced pulsation and vibration in hydroelectric machinery. Engineer’s guidebook for planning, design and troubleshooting (London: Springer)
[2] Tu S W and Ramanprian B R 1983 Fully developed periodic turbulent pipe flow. Part 1. Main experimental results and comparison with predictions Journal of Fluid Mechanics 137 pp 31-58
[3] He S and Jackson J D 2009 An experimental study of pulsating turbulent flow in a pipe European Journal of Mechanics B/Fluids 28 pp 309-320
[4] Sundström L J R and Cervantes M J 2018 On the similarity of pulsating and accelerating turbulent pipe flows Flow, Turbulence and Combustion 2018 96 pp 417-436
[5] Bergant A, Mavrič A, Tijsseling A, Hou Q and Svingen B 2015 Structural response of a pipeline apparatus to pulsating flow at resonance and non-resonance conditions Proceedings of the 6th IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems (Ljubljana) pp 169-176.
[6] Ferziger J H and Peric M 1999 Computational methods for fluid dynamics (Berlin: Springer-Verlag)
[7] Vardy A, Bergant A, He S, Ariyaratne C, Koppel T, Annus I, Tijsseling A and Hou Q 2009 Unsteady skin friction experimentation in a large diameter pipe Proceedings of the 3rd IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems (Brno) pp 593-602
[8] Tijsseling A S, Hou Q, Svingen B and Bergant A 2013 Acoustic resonance experiments in a reservoir-pipeline-orifice system Proceedings of the ASME 2013 Pressure Vessels & Piping Division Conference (Paris) Paper PVP2013-97534
[9] Bergant A, Gregorec J, Wahl T and Urbanowicz K 2018 Analysis of pulsating flow in a large-scale pipeline close to resonance conditions Proceedings of the 13th International Conference on Pressure Surges (Bordeaux) (Cranfield: BHR Group) pp 423-437
[10] Ariyaratne C, Wang F, He S and Vardy A E 2010 Use of hot-film anemometry for wall shear stress measurements in unsteady flows Proceedings of the 14th International Heat Transfer Conference (Washington) Paper IHTC14-22674
[11] Menter F R 1994 Two-equation eddy-viscosity turbulence models for engineering applications AIAA Journal 32 pp 1598-1605