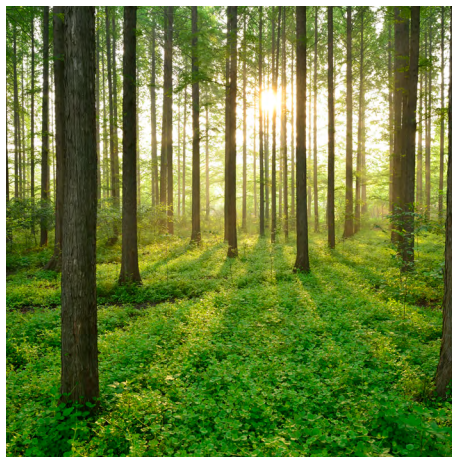
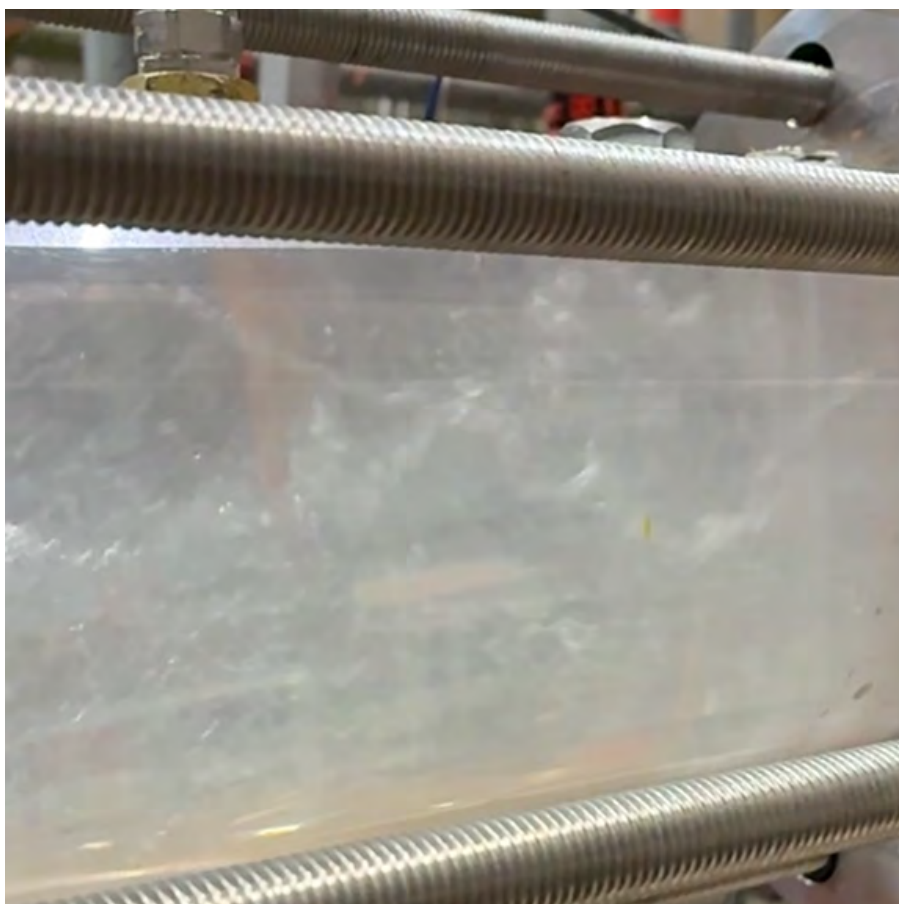


CAVITATION INDUCED VIBRATIONS IN VALVES

REPORT 2026:1194



VIBRATIONS IN
NUCLEAR APPLICATIONS



Cavitation induced vibrations in valves

Experimental data for CFD validation

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Foreword

Cavitation and flow-induced vibrations in valves are critical issues in piping systems, particularly in nuclear power plants, where reliability and structural integrity are essential. These phenomena can lead to fatigue damage, erosion, and reduced operational safety.

The purpose of this study is to experimentally investigate cavitation and flow-induced vibrations in partially closed valves, and to generate high-quality experimental data. This data is intended to support the validation and improvement of Computational Fluid Dynamics models.

The results show that strong cavitation significantly increases vibration levels, particularly for globe valves, while butterfly valves are less sensitive. The study provides valuable experimental data and improved understanding, supporting more reliable modelling and assessment of valve performance

This report forms the results of a project performed within the Energiforsk Vibrations in Nuclear Applications Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi. The Vibrations in program aims to increase the knowledge of causes, monitoring and mitigation of vibrations, thereby contributing to the safety, maintenance and development of a diverse range of machinery in the Nordic nuclear power plants.

The study was carried out by Kristian Angele, Vattenfall Research & Development.

These are the results and conclusions of a project, which is part of a research Program run by Energiforsk. The author/authors are responsible for the content.

Summary

The assignment includes to experimentally investigate flow induced vibrations (FIV) in valves, in order to provide experimental data for validation of CFD models.

FIV could be the result of large scale turbulent structures in the process fluid, which occurs due to major flow discontinuities such as bends, tees, bore connections, partially closed valves and orifices. If the vibration frequency is close to the structure eigen frequency this can lead to the excitation of vibration modes of the piping and connected equipment. This could potentially lead to fatigue cracking within a relatively short period of time. For large pressure losses through partially closed valves or orifices, cavitation can also appear, which can cause both vibrations but also erosion damages due to the implosion of the steam bubbles close to the walls when the pressure recovers downstream.

Today the phenomena of cavitation and FIV can be simulated using Computational Fluid Dynamics (CFD), however there are large uncertainties in the models and therefore experimental validation is needed.

The present work experimentally investigates FIV and cavitation in piping with partially closed valves, in order to provide experimental data for validation of CFD models. An existing setup with interchangeable valve geometries was used.

Keywords

Cavitation, orifice plate, valve, flow induced vibrations, experiment, CFD validation

Sammanfattning

I uppdraget ingår att experimentellt undersöka flödesinducerade vibrationer (FIV) i delvis stängda ventiler, för att kunna tillhandahålla experimentella data för validering av CFD-modeller.

FIV kan induceras i strömmande media på grund av storskaliga turbulenta strukturer och uppstår på grund av stora flödesdiskontinuiteter såsom rörböjar, T-stycken, delvis stängda ventiler och strypningar. Om vibrationsfrekvensen ligger nära strukturens egenfrekvens kan detta leda till excitation av vibrationer i rörledningarna och ansluten kringutrustningen. Detta kan potentiellt leda till utmattningssprickor inom en relativt kort tidsperiod. Vid stora tryckförluster genom delvis stängda ventiler eller strypningar kan även kavitation uppstå, vilket kan orsaka både vibrationer men även erosionsskador på grund av implosion av ångbubblorna nära väggarna när trycket återhämtar sig nedströms.

Idag kan fenomenen kavitation och FIV simuleras med Computational Fluid Dynamics (CFD), men det finns stora osäkerheter i modellerna och därför behövs experimentell validering.

Detta arbete undersöker FIV och kavitation i rörledningarna med delvis stängda ventiler experimentellt, för att tillhandahålla data för validering av CFD-modeller. En befintlig experimentuppställning med utbytbara ventilgeometrier användes.

List of content

1	Introduction	6
2	Method	8
2.1	Test rig	8
2.2	Instrumentation	8
2.3	Valve geometries	10
2.4	Test matrix and boundary conditions	11
3	Results	12
3.1	Stability, repeatability and statistical uncertainty	12
3.2	Pressure loss coefficient	12
3.3	Visualization of the cavitation	15
3.4	Vibration measurements	18
4	Conclusions	22

1 Introduction

In the present study cavitation induced vibrations are studied experimentally in partially closed valves. The purpose is to generate more detailed validation data for CFD-models.

A valve is used to regulate the flowrate in a pipe system by moving a part which restricts the flow by making the flow cross-section area smaller. There are numerous types of valves, *e.g.* check valves, which regulates the flow direction, *i.e.* only allows flow in one direction, ball valves, needle valves, knife gate valves, investigated in the previous study. In the present study a butterfly valve and a globe valve, which are used to vary the magnitude of the flowrate, are investigated.

The pressure loss over a valve which is partially closed, $\Delta P = P_1 - P_5$, is the difference between the pressure upstream (P_1) and downstream (P_5) of the flow restriction, where the pressure has recovered. The pressure loss coefficient, ξ , is defined as the pressure loss normalized with the dynamic pressure, where the bulk velocity, u , is calculated as the flowrate, Q , divided by the flow cross-section area upstream of the flow restriction, see eq. (1). The pressure loss coefficient is a function of the open area ratio, ϕ , *i.e.*, the cross-section area of the opening of the valve, A_o , in relation to the pipe cross-section area upstream, $A = \pi D^2/4$, Figure 1.

When the flow is accelerated through the smaller cross-section area of the flow restriction, the velocity and dynamic pressure increases due to continuity and the local static pressure is reduced as a consequence. Cavitation occurs when the flow restriction is small and the flow is accelerated so much that the local static pressure in the flow is reduced below the saturation or vapor pressure, $p_{sat.}$, and gas bubbles are generated.



Figure 1. The flow and cavitation through an almost fully closed knife gate valve.

$$\xi = \frac{\Delta P}{0.5\rho u^2} \quad (1)$$

$$\sigma = \frac{P - p_{sat.}}{\Delta P} \quad (2)$$

The cavitation number, σ , is often used to characterize the level or severeness of the cavitation and is defined as the local static pressure (often measured at the pipe wall), P , minus $p_{sat.}$, normalized with the pressure loss across the flow restriction, ΔP , eq. (2). When the cavitation number is low the cavitation is strong. Strong cavitation often leads to high vibration levels as the implosion of the gas bubbles generates large pressure spikes. This can cause fatigue and failure in the pipe system and also lead to erosion if the implosion of the bubbles occurs close to the pipe wall.

2 Method

2.1 TEST RIG

Within the framework of this study, the physical model from 2020 and 2025 has been re-built in the Älvkarleby Laboratory to be able to study the cavitating flow downstream of the valves under well-defined and controlled test conditions.

A photo of the test rig's piping and the instrumentation is shown in Figure 2. The pipe system is DN100 (102.7 mm inner diameter) made in pressure class PN10. The position of the valve and the downstream plexiglass pipe is also shown.

In the laboratory there is an rpm-regulated pump from Ringhals AB which takes municipal water at room temperature from a low basin of 300 m³ and provides a flowrate of up to 300 l/s or a maximum head of about 8 bar at full speed, 1500 rpm. The speed is varied here to set the desired flow rate and upstream pressure before the orifice plate.

In order to be able to vary the downstream pressure, the test rig contains an adjustable valve downstream of the orifice plate, V5.

2.2 INSTRUMENTATION

The pressure upstream (P1) and downstream (P5) of the orifice plate or the valve is measured with 10-bar pressure sensors with an uncertainty of about $\pm 0.5\%$ of full scale. The position of the pressure sensors in relation to the valve ($x=0$) is shown in Figure 2

The volumetric flow rate (Q) is measured with a KROHNE OPTIFLUX 4000 electromagnetic flow meter with an uncertainty of about $\pm 0.5\%$ of full scale. This has been calibrated up to 25 l/s. The diameter of 150 mm has been chosen so that the velocity will be 1-10 m/s at the nominal flowrate tested here in order to reduce the uncertainty in the measurement. The flow meter installation meets the requirements by KROHNE for how long a straight pipe should be before (5D) and after (2D) the electromagnetic flow meter so that it is not affected by secondary flow downstream of a pipe bend.

The temperature (T1) is measured with a Pt100 sensor with an uncertainty of about 0.1°C. The temperature is needed to calculate the vapor pressure and the density. The density is 998 kg/m³ and varies approximately 0.1% between 0-20°C.

The cavitation is visualized with a Photron FASTCAM Nova S high speed camera with a frame rate of 16000 fps.

A measurement system with 12 channels is used for the flowrate and the pressures and the data collection is done with LabView. The sampling rate is 100 Hz and the sampling time is about 1 minute.

The vibration levels are quantified with four accelerometers (DYTRAN ICP 100mV/g) measuring in three directions. They are placed upstream, close to the valve flange and also after the Plexiglas test section, see Figure 2. A separate measurement system is used for the vibration levels but they are synchronized with the hydraulic measurements.

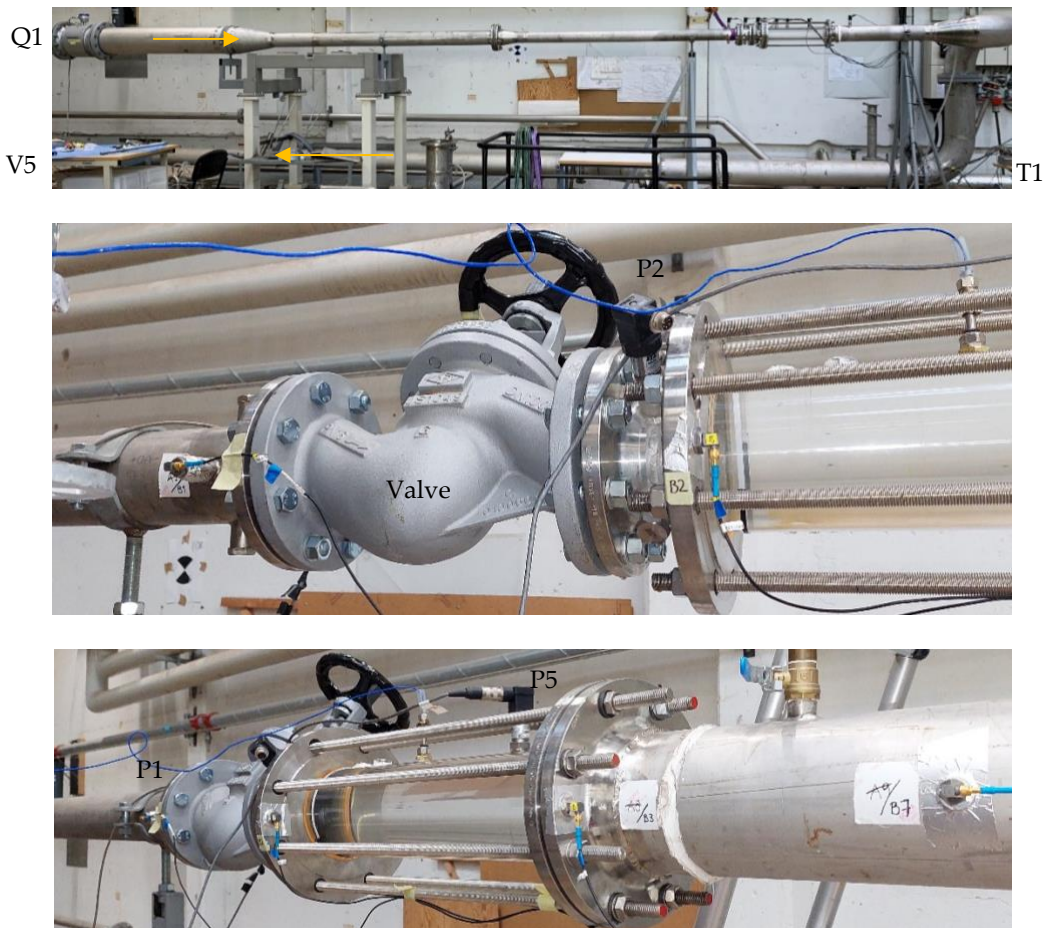


Figure 2. Photo of the test rig, Plexiglas test section and instrumentation positions.

2.3 VALVE GEOMETRIES

The geometry of the valves is shown in Figure 3.

The butterfly valve tested here has a circular disc supported on a rod (at the center of the pipe) which can rotate around its own axis so that the plate angle with respect to the oncoming flow, θ , can be varied seamlessly and ultimately cover the whole flow cross-section area and completely hinder the flow, see **Error! Reference source not found.** and Figure 6. The open area ratio is non-linear with the opening angle and can be approximated with $1-\sin(\theta)$, [2]. This type of valve is similar to the knife gate valve, but the fluid flows on both sides of the disc hindering the flow, as opposed to the knife gate valve, where the flow goes asymmetrically along only one side of the pipe.

The globe valve also has a plate which can cover the flow cross-section area, however, for this valve type the plate is perpendicular to the flow direction so the flow goes radially outwards through the gap width height, h , between the perpendicular disc and the seat. However, after that it turns to the main flow direction along the pipe wall. The open area ratio becomes linear with the height of the plate above the seat, $\phi=4h/D$ (note that h can also be measured outside the valve). When fully open, $h=27$ mm and open area ratio is equal to one as $D=100$ mm. The diameter of the inlet, outlet and seat of the globe valve is the same as the pipe diameter, *i.e.* DN100.

For both valve types tested here, the flow and cavitation occurs along the pipe wall similar to the knife gate valve and differently from the orifice plate, where the flow and cavitation occurs in the center of the flow, away from the pipe wall.

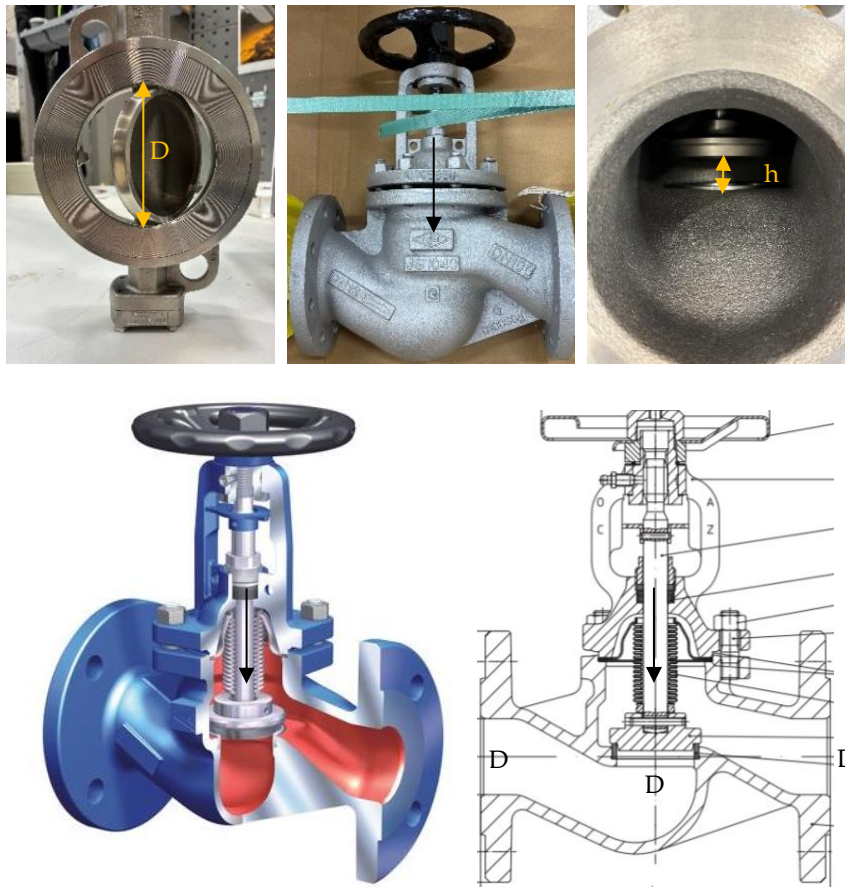


Figure 3. The butterfly valve and the globe valve.

2.4 TEST MATRIX AND BOUNDARY CONDITIONS

The tests are carried out with ordinary municipal water at room temperature (18°C slightly depending on the day and the ambient temperature outside the lab hall). The testing is performed in the same way as in the tests for the knife gate valve (“Stafsjö” valve) performed in 2025, [2], *i.e.* for each valve type, tests are performed with a constant pump speed (rpm) and a constant position of the valve V5 downstream of the test section. The valve is successively closed in separate tests, which reduces the open area ratio, increases the pressure loss coefficient and the pressure loss, which reduces the flowrate and the pressure downstream of the valve. This generates an increasing degrees of cavitation in the successive tests. This is then repeated for different constant pump speeds, 900 rpm, 1200 rpm and 1500 rpm (which corresponds to the maximum speed of the pump), which increases the upstream pressure and flowrate.

Note that the operation of the pump leads to vibrations in the pipe system, which are not flow (cavitation) induced. Relative comparisons between vibration levels can therefore only be made for the same pump speed.

3 Results

3.1 STABILITY, REPEATABILITY AND STATISTICAL UNCERTAINTY

The results from the tests show that the flow rate is stable within the measurement uncertainty. If you repeat the same test for the same conditions, you get essentially identical results in terms of measured pressures. The differences are within the measurement uncertainty. This indicates that the results are both repeatable and that the data are statistically converged with the measurement time of 1 minute.

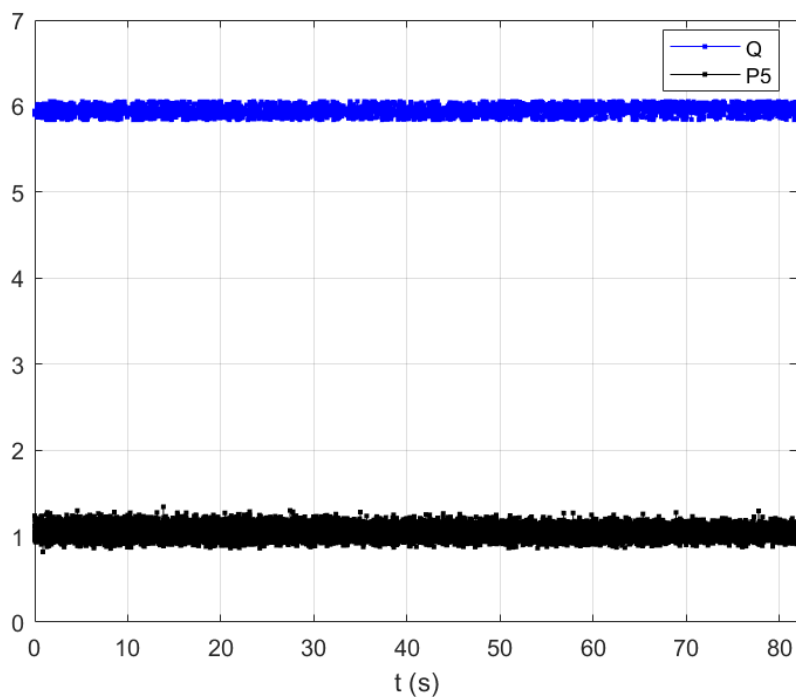


Figure 4. Flowrate and pressure downstream of the valve as a function of time.

3.2 PRESSURE LOSS COEFFICIENT

If one keeps the valve in a fixed position and change the speed of the pump one increases the flowrate and the pressure drop. Plotting the pressure drop against the dynamic pressure gives a linear trend where the inclination corresponds to the pressure loss coefficient, ξ .

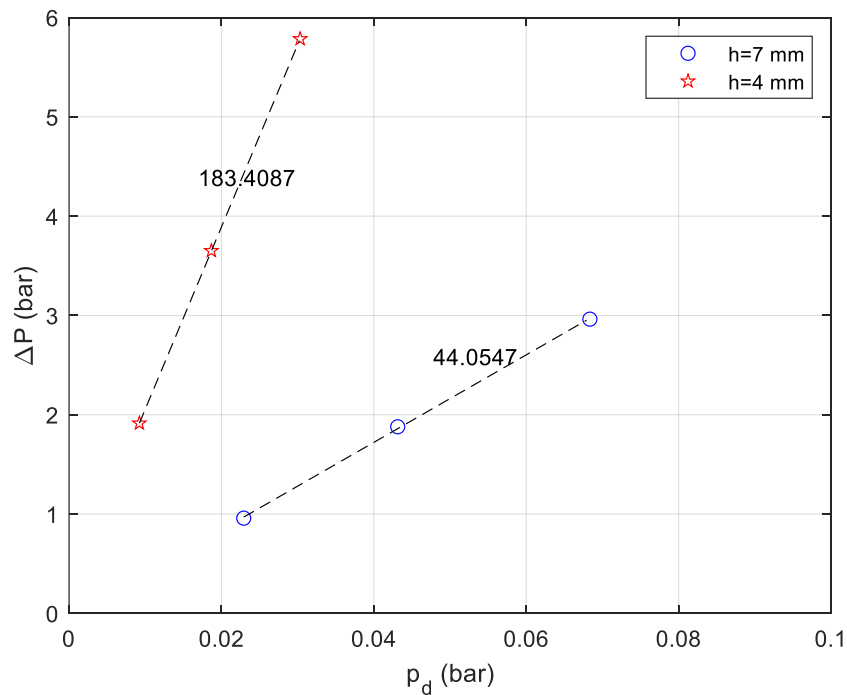


Figure 5. Pressure loss coefficient for the globe valve at two different positions.

If one performs tests for different positions for the globe valve and disc angles for the butterfly valve, see Figure 6, one can see how the pressure loss coefficient increases rapidly and nonlinearly with the open area ratio, Figure 7.

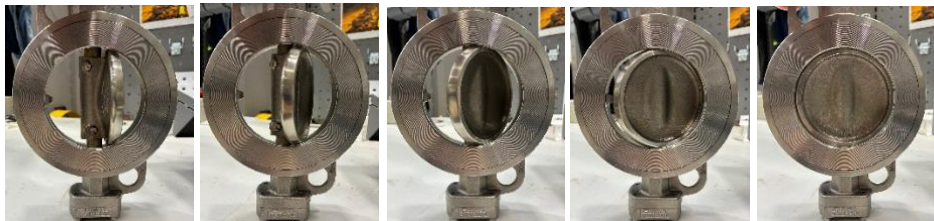


Figure 6. Butterfly valve at different opening angles, $\theta=0^\circ$ (fully open), 20° , 45° , 70° and 90° (fully closed).

The trend is similar independent of the type of valve (butterfly, cone or knife gate valve). The variation in ξ for the repetitions of the same valve position is most likely due to the difficulty in accurately setting the exact valve position and the strongly non-linear nature of ξ .

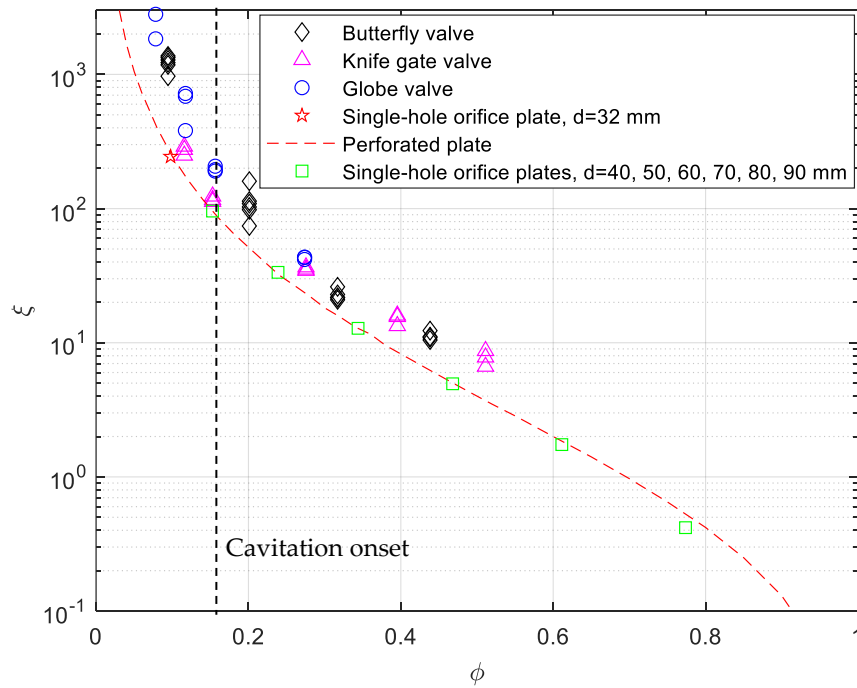


Figure 7. Pressure loss coefficient as a function of open area ratio.

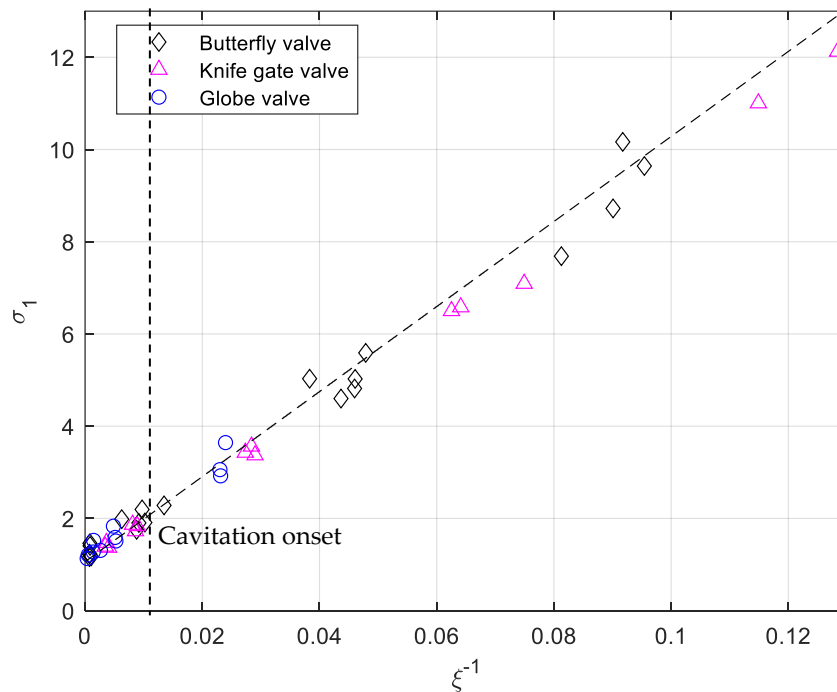


Figure 8. Cavitation number as a function of the inverse of the pressure loss coefficient.

If one plots the cavitation number against the inverse of the pressure loss coefficient one gets a similar linear trend independent of the type of valve, see Figure 8. The overall level of cavitation is therefore essentially given by

the pressure loss coefficient, given by the open area ratio and not by what type of valve that has generated it. If one starts closing the valve, the flowrate will be reduced, the pressure loss coefficient increases (its inverse decreases) and the level of cavitation increases (*i.e.* the cavitation number decreases). Onset of cavitation occurs around $\sigma_1=2$ *i.e.* when $\xi\sim 100$ and $\phi\sim 0.15$ for the cases measured here.

3.3 VISUALIZATION OF THE CAVITATION

Figure 9 shows the cavitation downstream of the globe valve at $h=2$ mm ($\phi\sim 0.08$) when the valve is almost closed. The flow is choked and increasing the pressure upstream from about 5.3 to 8.8 bar (1200 rpm to 1500 rpm pump speed) does essentially not have any effect on the flowrate, which increases only slightly from 5.9 l/s to 6.1 l/s.

Two longitudinal vortical structures are formed after the valve disc and they influence each other so that they become twisted around each other in a helical pattern downstream inducing a swirl in the flow.



Figure 9. Instantaneous vortical structures downstream of the globe valve.

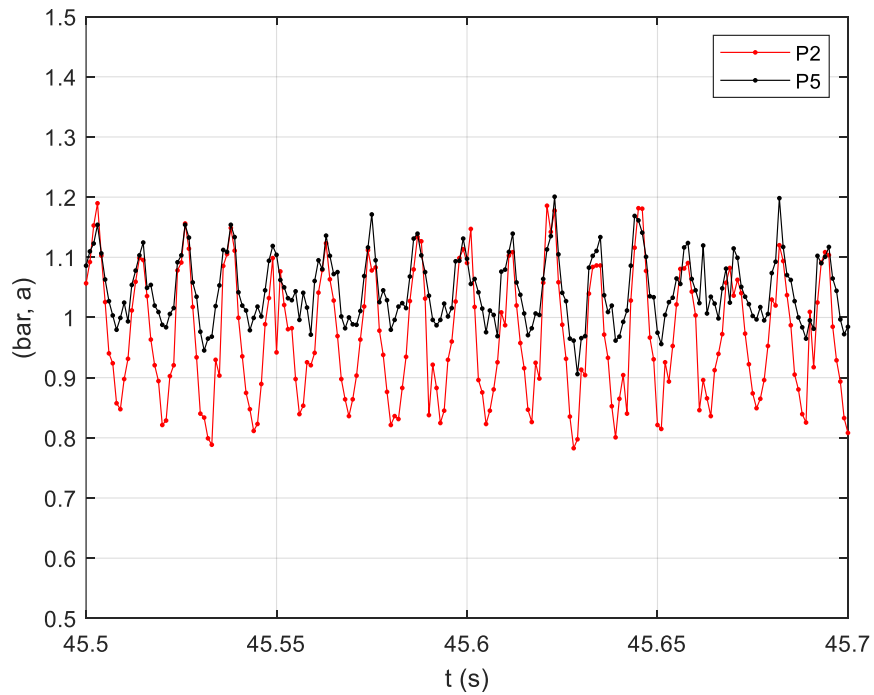


Figure 10. Periodic pressure variations downstream of the globe valve.

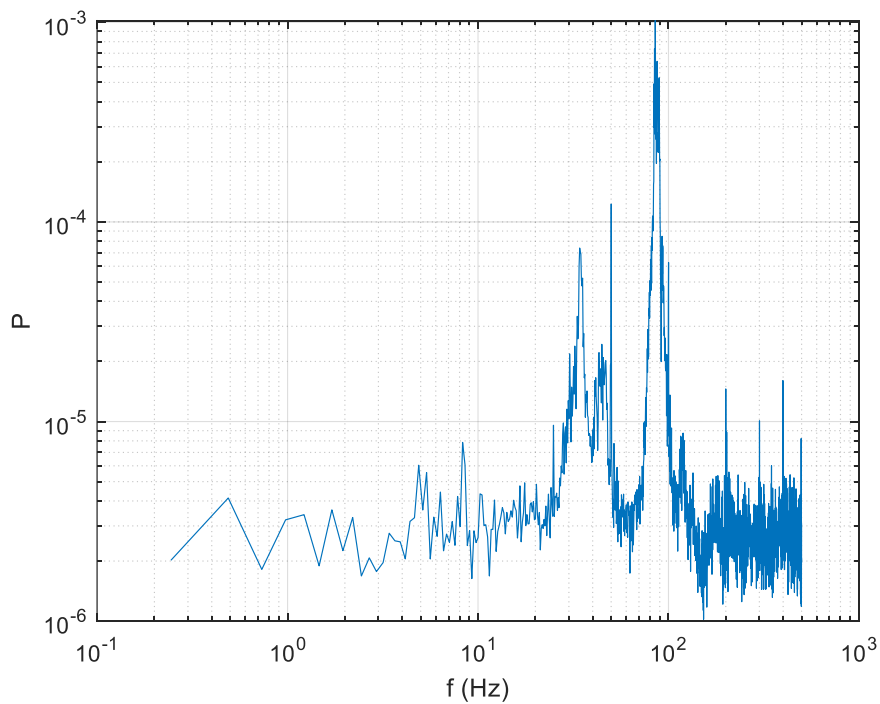


Figure 11. Spectrum of the pressure P2 downstream of the valve.

The time series of the pressure reveals the periodic variations in both pressure measurements downstream of the valve (P2 and P5) with a time

scale of slightly more than 0.01 s. The amplitude is larger in P2 closer to the valve (about $\pm 20\%$), but it is still visible in P5 at $x/D=4$, Figure 10.

The spectra of P2 show a clear peak with most of the energy at the preferred frequency of about 90 Hz, which corresponds to a $St=0.23$ (similar to the vortex shedding behind a circular cylinder), based on the height of the gap between the seat and the disc of the globe valve, $h=2$ mm, and the bulk velocity 0.75 m/s, see Figure 11.

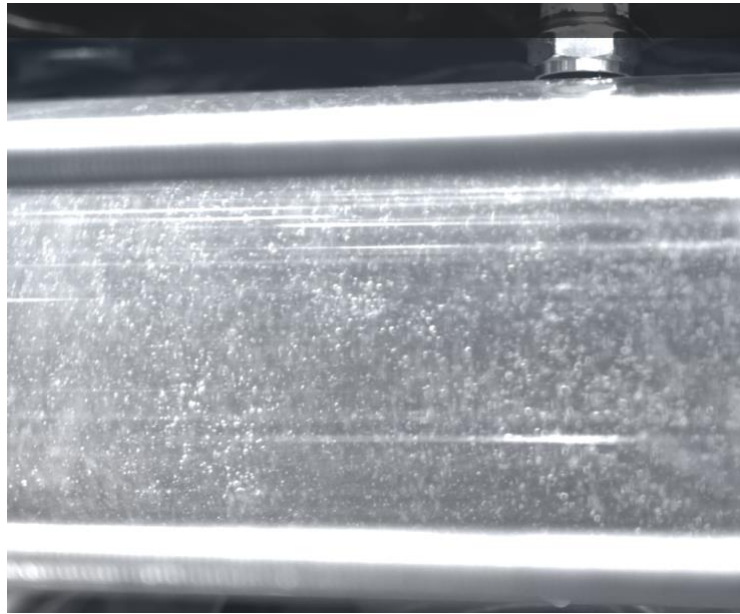


Figure 12. Instantaneous image of the small evenly distributed gas bubbles for the globe valve at choked flow conditions, $h=2$ mm.

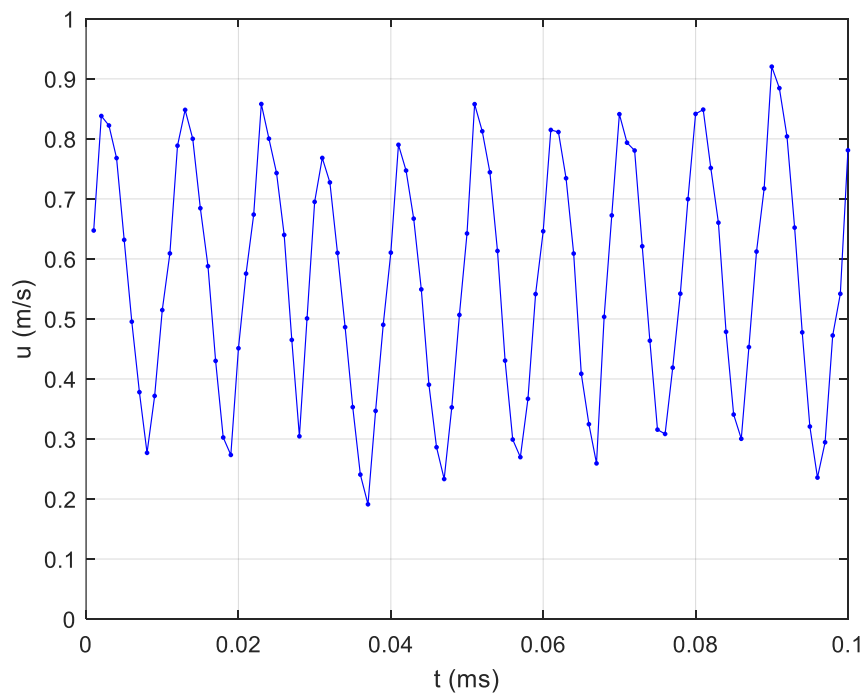


Figure 13. Periodically varying velocity downstream of the globe valve at choked flow conditions, $h=2$ mm.

High speed camera movies at 1 kHz indicate that the flow is pulsating. The subsequent image pairs of the steam bubbles were processed using a conventional particle image velocimetry (PIV) algorithm and the results reveal a varying velocity with a periodicity and amplitude similar to the pressure fluctuations, *i.e.* around 90 Hz. Note that the pulsating flow cannot be detected by the flowmeter, which has a too long response time (of the order of 1 s). The periodically varying flow could be caused by chattering of the valve disc, which oscillates and vibrates violently, perhaps even slamming against the valve seat. This is supported by a loud noise and large amplitude valve- and valve handle vibrations with the same frequency, see Figure 15.

3.4 VIBRATION MEASUREMENTS

The time series for the vibration sensors in the streamwise component also show a periodicity at about 0.011 s for the globe valve at choked flow ($h=2$ mm and $\sigma=1.13$), in line with the results for the pressure sensor and the flowrate, Figure 10 and Figure 13.

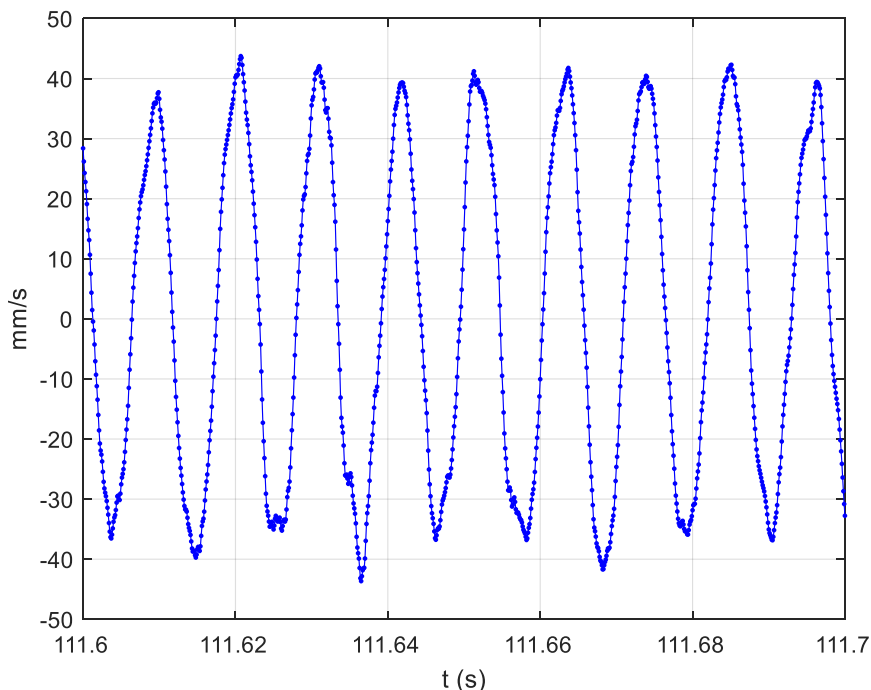


Figure 14. Time series of the vibration level in the streamwise direction for the cone valve at choked flow conditions ($h=2$ mm and $\sigma=1.13$).

The spectra for the vibration sensors therefore also show large peaks around 90 Hz in the streamwise component for the globe valve at choked

flow ($h=2$ mm and $\sigma=1.13$), in line with the results for the pressure sensor and the flowrate, Figure 15.

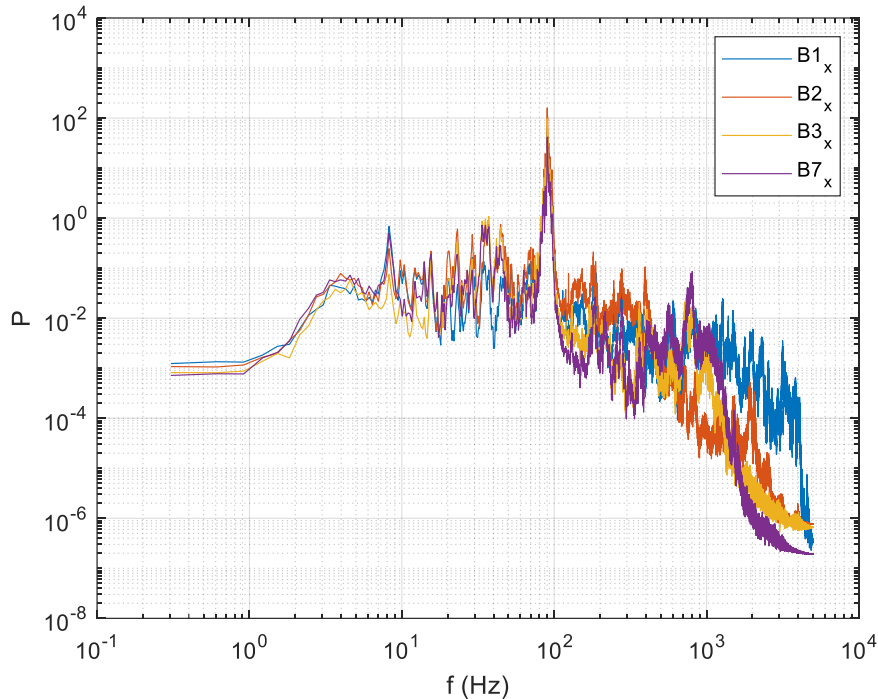


Figure 15. Spectra for the vibration levels in the streamwise x-direction for the cone valve at choked flow conditions ($h=2$ mm and $\sigma=1.13$), 1500 rpm.

All overall vibration levels increase with the pump rpm (*i.e.* pump power or head and flowrate) as has been observed in all similar preceding studies in the same test rig, see Figure 16. The vibration levels essentially scale with the dynamic pressure *i.e.* the square of the rpm.

The vibrations for the globe valve increase rapidly with the level of cavitation whereas the butterfly valve seems comparatively insensitive to cavitation, see Figure 17. This holds for all measurement points in all three measurement directions. Note that when the valve is successively throttled, the flow rate is reduced so the dynamical pressure decreases. If one would scale the data below taking this into consideration, the trend would be even more pronounced.

The spectra without and with cavitation, Figure 18 reveal that the low frequent energy in the vibrations (~ 10 Hz) originates from the pipe system itself whereas the cavitation exists in the higher frequency range ($\sim 10^2 - 10^3$ Hz). This is similar to the orifice plate investigated before, [1].

The resonance-like phenomenon where the magnitude of the flowrate and the extent of the gap between the disc and the seat of the valve is such that the a flow instability with frequency of 90 Hz most likely coincides with the

eigen frequency of some part of the structure in the present test rig is a unique case. It is conjectured that this leads to a chattering-like oscillation where the valve disc vibrates violently causing the flow and pressure to pulsate and the whole test rig to vibrate at 90 Hz.

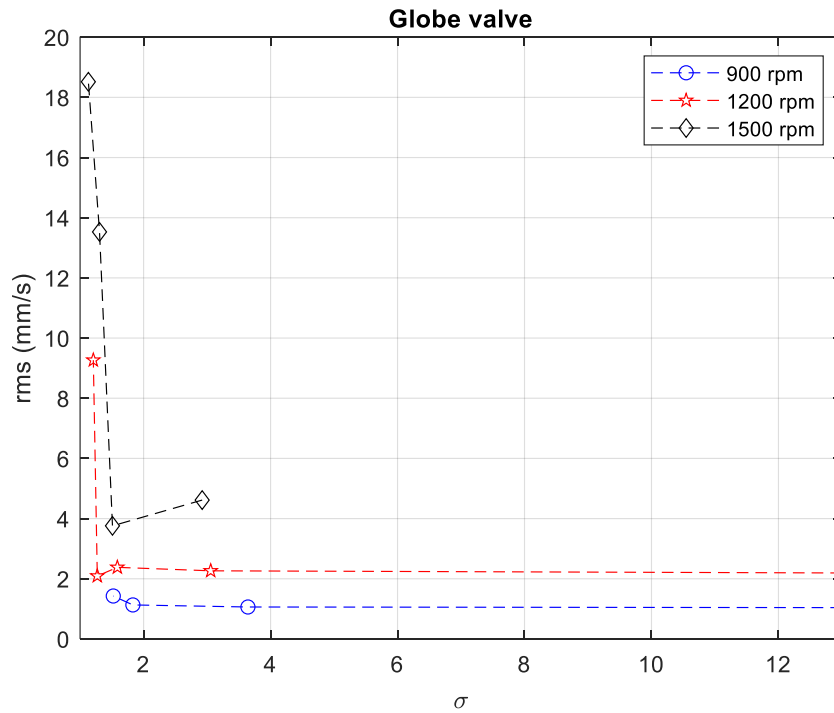


Figure 16. Vibration level as a function of the cavitation number for the globe valve.

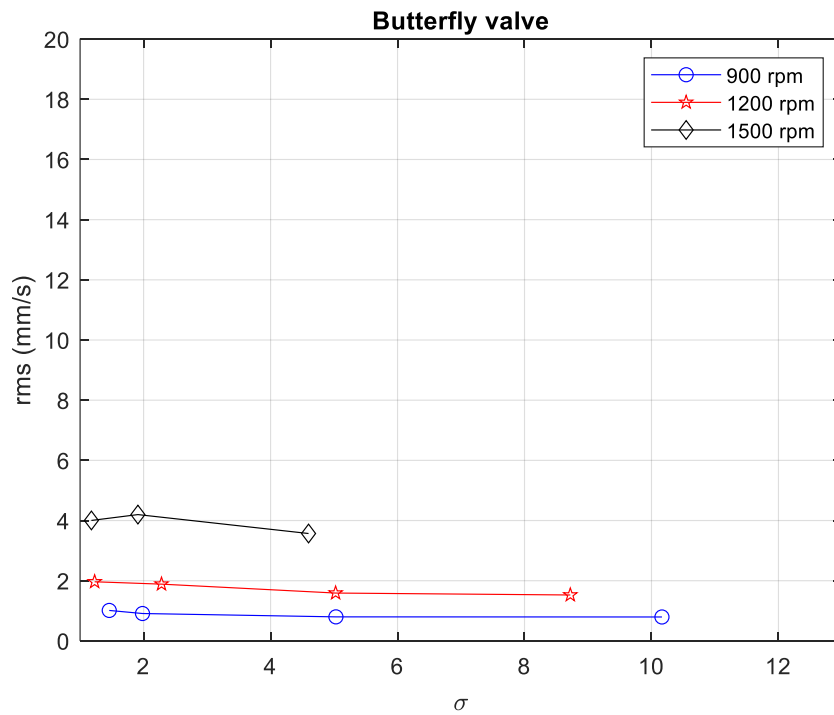


Figure 17. Vibration level as a function of the cavitation number for the butterfly valve.

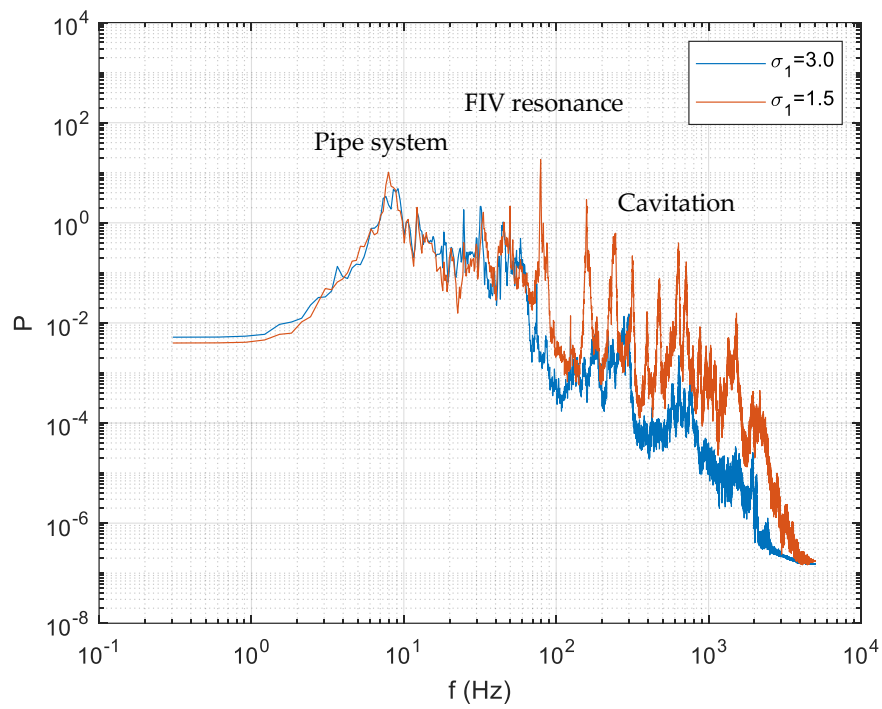


Figure 18. Spectra for the vibrations in the y -direction for the cone valve without cavitation ($\sigma=3.0$) and with moderate cavitation ($\sigma=1.5$) at 1500 rpm.

4 Conclusions

The flow through throttled valves, which are almost closed, leads to a large value of the pressure loss coefficient, a large pressure drop and strong cavitation. The cavitation, in turn, leads to high vibration levels.

Two different types of valves have been investigated, a globe valve and a butterfly valve.

The vibrations for the globe valve increase rapidly with the level of cavitation whereas the butterfly valve seems comparatively insensitive to cavitation.

These new data can be used for the validation of more advanced CFD models.

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CAVITATION INDUCED VIBRATIONS IN VALVES

For flows through partially closed valves at large pressure losses, cavitation can appear, which can cause both vibrations and erosion damages due to the implosion of the steam bubbles close to the pipe walls when the pressure recovers downstream.

Today the phenomenon of cavitation can be simulated using Computational Fluid Dynamics (CFD), however there are large uncertainties in the models and therefore better experimental validation is needed.

The present work experimentally investigates cavitation induced vibrations in pipes with partially closed valves using modern measurement techniques in order to provide new experimental data for validation of CFD models.

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