High precision manufacturing machines often require extremely tight tolerances in their end products. Hence vibrations induced by flow within internal components such as an orifice, can cause deviations in measurements and defects in production. These vibrations caused due to orifices are a result of large pressure drops generated during flow separation resulting in pressure waves that propagate within the system interacting with other components. In this article vibrations resulting from orifice flows are comprehensively studied through a series of experiments and numerical simulation. The experiments performed involve pressure measurements with varying orifice diameters. The pressure signals obtained from the experiment are recorded and analysed with respect to their energy distribution. The study is further extended to analyse the effect of orifice diameters on pressure fluctuations, and in the process also observe and identify the phenomena of cavitation. To obtain a more detailed understanding of the flow and the underlying behaviour, a Large-Eddy Simulation (LES) of orifice flow is performed for a selected orifice. The LES results are validated using different databases involving previous studies and the experiments that have been performed. The LES results are analysed in detail with regards to the spectral characteristics of velocity and pressure fluctuations using mathematical tools such as Fourier Analysis. The results provide an insight on the flow development, energy distribution and power spectrum distribution in the flow.

Keywords: FLOW INDUCED VIBRATIONS, ORIFICE FLOWS, CAVITATION, LARGE EDDY SIMULATION

1. Introduction

An orifice is an extensively used component for purposes of flow measurement devices or as a flow rate control device functioning as a restriction. An orifice installed in a system leads to flow separation resulting in a sudden drop in static pressure which later stabilizes to a downstream pressure. In flow meters
orifices are mainly characterized by their coefficient of discharge $C_D$. However, creating large static pressure drop across an orifice generates undesirable flow characteristics as a consequence. Separated flow regimes, generates vortices which are convected downstream, leading to a highly turbulent region. The turbulence generated close to the orifice generates large fluctuations in pressure which can act as a source of acoustic disturbance throughout the circuit which has also been seen in the study by [2].

[3] studied the effect of Reynolds number and orifice diameters on pressure fluctuations downstream of the orifice in large water pipes. The study shows the development of turbulent pressure fluctuations as it advects downstream of the orifice plate. The relations between flow and turbulent pressure can be better analyzed through numerical simulations. However to investigate small scale and high frequency behaviour of flow, CFD simulations using statistical time averaging equations like RANS can no longer be used. A more powerful CFD tool is required to resolve these equations. High fidelity CFD simulations like LES and DNS are capable of resolving the flow dynamics to extremely small scales and therefore are capable of simulating high frequency pressure and velocity fluctuations.

In the current study the focus is on characterisation of the pressure fluctuations and their development downstream of the orifice plate. The work was split into experimental and numerical parts. The first portion involves experiments for pressure measurements and analysis. This is followed by LES and its comparison to experimental results.

2. Experiments

The experimental test is designed to capture the pressure fluctuations observed within the fluid circuit at certain discrete positions. The test setup used in the study is similar to the setup used by [4] to check the effect of orifice on the pressure fluctuations in the upstream and downstream of the orifice. The test set-up involves a closed circuit in which water is pumped from a tank through a PU (Poly-Urethane) with an inner diameter, $D = 9$ mm and thickness of 1.5 mm. The PU pipes are maintained to sufficiently long to damp out high frequency pressure fluctuations originating from the pump. The overall circuit diagram of the experimental setup can be seen in figure 1. The probes P1, P2, P3, P4, and P5 shown in figure 1 are pressure transducers which are connected to DAC (Digital to Analog Converter).

A close up view of the main test section is shown in figure 2. The upstream section is a smooth straight pipe with inlet diameter $D = 9$ mm and length of 300 mm followed by the orifice. The downstream section has a pipe length of 200 mm. The pressure transducers P1, P2, P3, P4, and P5 (in figure 1) are placed at distances $-2D$, $1D$, $2D$, $3D$ and $6D$ with the orifice as the origin and the flow direction being the positive direction.

The orifice plates are interchangeable within the setup. In the current study four different types of
Orifices

orifices have been studied. The orifices can be characterized by non dimensional parameters such as porosity ($\beta$) and thickness ratio ($\eta$) defined as,

\[
\beta = \frac{A_h}{A_p} \quad \quad \quad \quad \quad \eta = \frac{t_o}{D_o}
\]

where $A_h$ is the hydraulic area of the orifice, $A_p$ is the area of the pipe, $t_o$ is the thickness of the orifice plate and $D_o$ is the diameter of the orifice. The tests are performed for all the orifices at flow rates for similar pipe Reynolds number, $Re_p$. The summary of orifice dimensions and flow conditions are provided in table [1].

<table>
<thead>
<tr>
<th>Orifice plate</th>
<th>Orifice Diameter $D_o$ (mm)</th>
<th>porosity $\beta$ (%)</th>
<th>thickness ratio $\eta$</th>
<th>Average velocity $\text{m/s}$</th>
<th>Reynolds number</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>2.00</td>
<td>4.94</td>
<td>0.5</td>
<td>0.93</td>
<td>8370</td>
</tr>
<tr>
<td>O2</td>
<td>3.00</td>
<td>11.11</td>
<td>0.5</td>
<td>1.22</td>
<td>10980</td>
</tr>
<tr>
<td>O3</td>
<td>5.00</td>
<td>30.86</td>
<td>0.5</td>
<td>1.26</td>
<td>11344</td>
</tr>
</tbody>
</table>

Table 1: Orifice plate dimensions and configurations used for the experiments.

3. Spectral behaviour of pressure fluctuations

The pressure signal obtained from the pressure transducers is the fluctuating pressure obtained by subtracting the mean pressure from the total pressure at the given position for orifice O3. Note that henceforth the fluctuating pressure, $p'$, then mean pressure and the absolute pressures will be denoted by $p'$, $\bar{p}$ and $p$ respectively. The analysis of the signal is performed by plotting the power spectral density curves and comparing the signals in frequency domains. The power spectral density denoted by $\Phi_{pp}$, is calculated for each sensor position and compared.

[5, 6] in their studies have clearly shown that for a turbulent shear free flow the pressure spectra follows the $-7/3$ law. According to which at high Reynolds numbers, the inertial subrange of the pressure spectra decays with a rate proportional to $\sim k^{-7/3}$, with $k = 1/l$ and $l$ being the eddy length scale. However, close to an orifice the flow is dominated by shear forces and hence the $-7/3$ law is not applicable in such situations. [7] in their article suggest a broader classification on the decay rates of the pressure spectrum, they state that in flow regions containing high mean shear-turbulence interaction, the spectrum follows a decay rate $\sim k^{-11/3}$. In figure 3(a–b) it can clearly observed that for locations close to the orifice, namely $x/D = 1$ the follows the $\Phi_{pp} \sim k^{-11/3}$ curve. Whereas at location $x/D = 6$ the inertial region of the spectra follows the $\Phi_{pp} \sim k^{-7/3}$ slope line closely. The power spectrum can
then be further integrated to calculate the RMS (root mean square) of the fluctuating pressure \(p_{rms}\) at every location. Figure 3c shows the evolution \(p_{rms}\) as the flow progresses downstream. The results in figure 3c also follow the similar trends as shown by [3] where the authors have also performed similar experiments to quantify the pressure fluctuations within an orifice. Figure 3c also shows the comparison of the normalized \(p_{rms}\) from the experiments to the data from [3]. The normalization of \(p_{rms}\) is performed similar to study by [8] for scaling of \(p_{rms}\) as follows,

\[
p_{rms}^* = \frac{p_{rms} D}{\rho U_o^2 d}
\]  

(2)

Figure 3c shows a good match of the \(p_{rms}^*\) with [3], however due to lack of data at position 0.5 \(D\) for the experiments in the present study, the values are not comparable.

4. Effect of Orifice diameters on pressure fluctuations and cavitation

The experiments are with performed three types of single hole orifices varying in diameters and thickness, the details of which have already been provided in table 1. In all the test cases the flow rates are maintained to be similar with a pipe Reynolds number \(Re_p \approx 10000\) as given in table 1. Figure 4 shows the comparison of the power spectrum plot between \(Re_p \approx 10000\) as given in table 1. Figure 4 shows the comparison of the power spectrum plot between the orifices O1, O2 and O3. The power spectrum shows a strong correlation between the orifice diameters and the turbulence generated from the orifices. Smaller orifices are observed to generate higher amplitudes of pressure fluctuations compared to larger ones for a given \(Re_p\) which is consistent with the findings of [3].

An important observation in figure 4 are the sharp high amplitude peaks that appear at certain fixed frequencies for O1 and O2, these frequencies are the harmonics starting from some initial first mode. Secondly, while conducting the experiments there is also a loud whistling noise that was noticed for these particular orifices. These two observations is an indication of cavitation occurring within the system. A way to identify a cavitating flow is by calculating the cavitation inception number, \(\sigma\). The cavitation inception number is a dimensionless number which can be calculated as follows,

\[
\sigma = \frac{P_{down} - P_v}{\frac{1}{2} \rho U_o^2}
\]  

(3)
where \( P_{down} \) is the downstream pressure, \( P_v \) is the vapour pressure of the liquid, \( U_o \) the average flow velocity at the orifice and \( \rho \) the density of the fluid. The cavitation inception number provides a threshold below which the flow starts to transition from a single phase to two phase flow, also \([9]\) in their study showed that for a for a given orifice the cavitation inception number remains a constant and does not change with fluid velocity \( U_o \). In the experiments conducted the vapour pressure of water for an ambient temperature of 298 K is \( P_v = 3.169 \) KPa. From the available experimental data, the cavitation inception number is calculated to be \( \sigma = 0.71 \) for O1 and \( \sigma = 2.2 \) for O2. The value of \( \sigma \) for O1 is significantly lower to the threshold value of \( 1.7 - 2.4 \) from the experiments performed by \([9]\) indicating a two phase flow. For O2, \( \sigma \) lies within the range of \( 1.7 - 2.4 \), which suggests a transition from the single to two-phase flow. The conclusion is bolstered by comparing the non-dimensional whistling frequencies to the observations given by \([10, 11]\) in their studies. The Strouhal numbers associated with whistling frequencies of a cavitating flow lie in the range of \((0.18, 0.26)\). Therefore the Strouhal numbers calculated as follows,

\[
St_o = \frac{f t_o}{U_o} \in (0.18, 0.26)
\]

where \( f \) is the whistling frequency. This can be observed in figure 5.
5. LES of Single Hole Orifice (O3)

A high fidelity numerical simulation such as Large Eddy Simulation (LES) is ideal for capturing the low to high frequency fluctuations in pressure and velocity fields within a turbulent flow. LES was first developed by [12] to resolve the large to inertial scale wave numbers for turbulent fluctuations, the remaining viscous sub layer region of the flow is modelled using sub-grid scale (SGS) models.

![Figure 6: Dimensions of computational domain used in LES. The figure shows the Front View (left) and the Side View (right) of the computational domain](image)

The domain consists of a cylindrical domain with a restriction in between to simulate an orifice as shown in figure 6. The distances are normalized with pipe diameter $D$ and the origin is placed at the downstream face of the orifice. A development length of $20D$ in the upstream of the orifice to ensures fully developed turbulent flow. The orifice restriction is kept 5 mm in diameter. The thickness of the orifice is $0.5D_o$ as in table I. The left boundary of fluid domain is given a velocity inlet boundary condition with inlet velocity $v = 1.24$ m/s and outlet of fluid domain is at constant outlet pressure of 0 Pa. The remaining surfaces are considered to be walls with no-slip boundary condition. At the flow inlet an additional synthetic turbulence is added to the mean flow to initiate the development of a turbulent boundary layer.

The fluid domain mesh consists of polyhedral mesh cells with geometrically increasing cell size from the wall to the centre of the pipe. The wall of the fluid domain is lined with a hexahedral prism layer to fully resolve the boundary layer of the flow. The first layer thickness of the mesh is maintained such that $y^+ < 2$. The mesh cell density is greatly increased at the orifice between the regions from $x/D = -1$ to $x/D = 2$ to resolve the smaller eddy scales due to large shear forces and turbulence. The total number of mesh cells in the fluid domain are $18 \times 10^6$. The flow equations were solved in the space using a segregated solver discretized with Bounded-Central differencing method with an upwind factor of 0.15. The SGS model used for modelling the high wavenumber fluctuations is the Wall Adapting Local Eddy viscosity (WALE) model [13]. The flow resolved in the time domain using an Implicit solver with $2^{nd}$ order time stepping scheme. The time steps is calculated based on the CFL condition [14], in all the case the Courant number, $Co \leq 0.3$. This is necessary to ensure convergence of the solution.

5.1 Simulation Results

The values of pressure are recorded from the LES as a continuous time signal. The PSD plots of the fluctuating pressure from experiments are then compared to that of LES at each axial position. The PSD plots of the LES are compared to the experiments at axial locations, $x/D = [-2, 1, 2, 3, 6]$ in figure 8(a–e). The comparison of PSD show a good agreement between the experimental numerical
results. It is important to notice that the decay rates of the power spectrum in each case conforms well with literature [7] and the experiments.

The root mean square pressure fluctuations along the $x/D$ direction between the LES and experiments are also compared. A frequency bandwidth of $10 \leq f \leq 51000$ Hz is selected as an overlap region between the two pressure signals and $p_{rms}$ was calculated. Figure 8f shows the development of $p_{rms}$ of the LES and the experiments between the mentioned frequency bandwidth from axial positions $-5 \leq x/D \leq 8$. A similar trend for decay of $p_{rms}$ can be observed in the axial direction from the comparison between the curves. The large deviation can be seen in the upstream region is due to a higher contribution to $p_{rms}$ in the frequency bandwidth $10 \text{ Hz} \leq f < 100 \text{ Hz}$ at the PSD in the axial position $x/D = -2$.

6. Summary and conclusion

Experiments were performed to understand the behaviour pressure fluctuations due to orifice, the orifices O1 and O2 were found to be cavitating and hence the focus was shifted to O3. Experiments and LES of the orifice flow was performed for orifice O3. The results are compared to pressure measurements that are performed previously. The results of the LES and experiments show a good agreement with each other. The pressure spectrum and cumulative $p_{rms}$ were the main comparison parameters in this case. This provided a great deal of insight on the flow and the flow structures and how the behaviour of turbulent pressure fluctuations are affected with flow. The study can be further extended to other types of orifices and perform characterization of each restriction type on the pressure fluctuations.
References


