Dynamic characteristics of orifice flowmeter impulse response based on CFD simulation

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Abstract

Because of its simple structure and ability to measure in reverse, orifice flowmeters are widely used in petroleum, chemical and other fields. In the measurement, the pipeline flow state instability occurs, which has a greater impact on the measurement performance of the orifice flowmeter. In order to study the influence of dynamic flow on the dynamic characteristics of orifice flowmeter. Based on CFD simulation, the dynamic characteristics of orifice flowmeter with different throttling ratio (β) under sinusoidal pulsating flow conditions is studied. Through the simulation of the internal flow field of the orifice flowmeter under the conditions of 7 different frequencies and 4 different amplitude combinations, the differential pressure values under different working conditions are extracted to analyze the amplitude-frequency characteristics and phase-frequency characteristics. The results show that the frequency has a great influence on the dynamic characteristics of the orifice flowmeter. At the throttling ratio is 0.2, the flow rate is 6 m^3/h and the amplitude is 1.2m^3/h, the orifice flowmeter amplitude-frequency characteristic linearity is as low as 1.9860%, phase difference is as low as -7.56°.

1. Introduction

Orifice flowmeter has the advantages of simple structure, no mechanical inertia, can measure the flow in forward and reverse direction, can measure high temperature and high pressure media, etc. It is widely used in process control and measurement in petroleum, chemical industry, water supply and other fields[1]. Orifice flowmeter occupies an important position in saving energy, improving product quality and increasing economic efficiency[2]. As the power pumps used in the petroleum and chemical industries are piston pumps, electromagnetic pumps, peristaltic pumps and other power pumps whose output is pulsating output. In flow measurement, non-constant pulsating flow conditions are prevalent. Orifice flowmeters are not used for steady-state flow measurement, but for pulsating flow measurement. This can cause the instantaneous flow characteristics of the orifice flowmeter to deviate from the theoretical analysis. Therefore, it is necessary to study the dynamic characteristics of the orifice flowmeter.

In recent years, there are many domestic and international studies on the dynamic performance of impulse response of orifice flowmeter. As early as the 1820s, researchers described pulsating flows and showed the difficulty of measuring them accurately[3]. The response of orifice flowmeters and venturi nozzle flowmeter in pulsating flows was studied by Mottram et al[4]. They proposed a method based on a modified theoretical analysis. Gajan et al[5](1992), did a study on the response of an orifice flowmeter under pulsating flow. They found that the orifice flowmeter outflow coefficient is sensitive to the velocity change upstream of the orifice plate and the throttling ratio. Muhammad et al[6]. carried out a study on the performance of orifice flowmeters under pulsation. They proposed a simple pulsating flow model for orifice flowmeter, which can reduce the sampling error by making a reasonable choice of the averaging time. Reis et al[7](2017). studied the effect of pulsation variation and time inertia of incompressible pulsating flow at low Reynolds number on the outflow coefficient of an orifice flowmeter. They found that inertia effects significantly affect the orifice flowmeter outflow coefficient. Guihua et al[8](2019). analyzed the instantaneous pressure-flow rate characteristics of an orifice flowmeter under sinusoidal input with the help of CFD method. The results show that the differential pressure and the instantaneous flow rate of the throttle orifice are in the same frequency and different phases, and the differential pressure amplitude increases linearly with the increase of the amplitude of the inlet flow rate. Brahma et al[9]. built a pulsating flow device to study the pulsating flow measurement of an orifice flowmeter. The outflow coefficients were found to range from (0.2-0.6) for measurements at different flow rates and pulsation frequencies. Tomasz et al[10]. investigated a testbed-based method for measuring pulsating flow in pipes. This method estimates the effect of key parameters (such as temperature, pressure and pulsation frequency or orifice plate flow) on the amplitude and frequency characteristics by varying these parameters. Brahma et al[11](2021). collected pulsation frequency, mass flow and pressure data for 77 working conditions. By analyzing the data, they proposed a pulsating flow steady-state method based on data estimation.

Currently, domestic and international research is to add pulsating flow on the orifice flowmeter, to derive the effect of pulsating flow on the outflow coefficient of the orifice flowmeter or to reduce the error of the orifice flowmeter. The dynamic characteristics of the orifice flowmeter under pulsating flow were not analyzed by the data. In this paper, orifice flowmeter with different throttling ratio was simulated by CFD simulation technology. The internal flow field data of the orifice flowmeter under different frequency and amplitude conditions is obtained. The differential pressure values at different flow rate are extracted. The amplitude-frequency characteristics and phase-frequency characteristics of orifice flowmeter are analyzed.

2. CFD Simulation

2.1 Simulation model building

DN30 orifice flowmeter is selected as the research prototype, and its structure is shown in Figure 1.

Figure 1 Orifice flowmater physical picture

The key parameters are shown in Table 1.

Table 1 Orifice flowmeter key parameters

Diameter (mm)	Aperture (mm)	Thickness (mm)	Bevel angle（°）
DN30	6	3	45°
	12		
	18		

In order to make the fluid reach the flowmeter is fully developed flow state, add 5D and 10D straight pipe section upstream and downstream of the orifice flowmeter respectively. The simulation model is shown in Figure 2

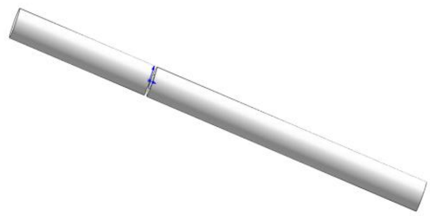


Figure 2 The simulation model

2.2 Grid independence verification

After the orifice flowmeter model is established, the flow field is meshed in Gambit. Due to it is necessary to study the pressure change the front and the back of the orifice flowmeter, unstructured grid with a mesh size of 1.5 is used in the orifice plate region. The straight section region adopts structured grid, and the grid size is 2, The total number of grids is 1.5million. The meshing results are shown in Figure 3.

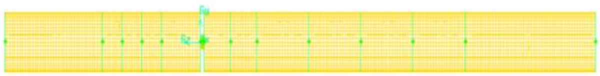


Figure 3 Mesh generation results of orifice plate three-dimensional simulation

In order to accurately predict the pressure change the front and back of the orifice flowmeter, the effect of grid number on the simulation results was investigated. Draw simulation models with a total number of meshes of 1.5million, 2.0million and 6.5million respectively. The simulation results are shown in Figure 4.

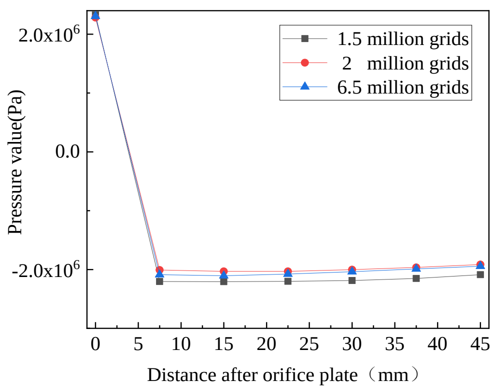


Figure 4 Simulation results of models with different grid numbers at different distances from the back of the orifice flowmeter

It can be seen from Figure 4, when the number of grids changes, the pressure values at each position back of the orifice flowmeter do not change obviously. In order to facilitate the simulation calculation, the model with the least number of meshes is selected for simulation.

2.3 Turbulence model selection

Turbulence model has great influence on a series of studies such as calculation of flow properties, velocity changes and pressure changes[12].As a non-standard part, orifice flowmeter has no experimental data to compare with simulation results. According to experience, the Standardk-ε model was selected for calculation. Standard k-ε model for simple flow field model the convergence rate is faster and the accuracy is higher when calculating the simple flow field model.

2.4 Unsteady simulation method

The UDF programming method is used to implement the sinusoidal pulsation input. The sine pulsation input pass equation is as in Equation 1.

$$\begin{cases} u = u_0 & t < 1 \\ u = u_0 + u_r \sin\left(2\pi f\left(t-1\right)\right) & t \geq 1 \end{cases} \quad (1)$$

u_0 is input velocity , u_r is input velocity disturbance f is input frequency. The working conditions are shown in Table 2

Table 2 Parameters of each working condition

β	Input		
	Flow rate（m³ /h）	**Amplitude (m³ /h)**	***f*(Hz）**
0.2/0.4/0.6	3/6	0.3/0.6/0.9/1.2	5
			10
			15
			20
			30
			40
			50

2.5 Simulation results

According to the working principle of orifice flowmeter, the flow equation of orifice flowmeter is shown in Equation 2:

$$q_v = \frac{\pi}{4} d^2 \cdot \frac{C_\varepsilon}{\sqrt{1-\beta^4}} \sqrt{\frac{2\Delta p}{\rho}} \quad (2)$$

q_v --Flow rate through the orifice flowmeter, m^3/h;

d --The diameter of orifice ,m;

C --Outflow coefficient, dimensionless;

ε --Expansion coefficient, dimensionless;

β --The ratio of orifice diameter d to pipe diameter D;

Δp --Differential pressure of measured fluid at the front and back pressure taps of orifice plate,Pa;

ρ --Fluid density, kg/m^3;

It can be seen from Equation 2 that,when the other parameters are kept constant, the differential pressure front and back of the orifice flowmeter will change when the flow rate changes.

Under the working condition with a throttling ratio of 0.4, a flow rate of 6 (m³/h), an amplitude of 0.6m³/h, and a pulsation frequency of 5 Hz. The pressure of the orifice flowmeter front 1.5D and back 0.5D、1D was studied.

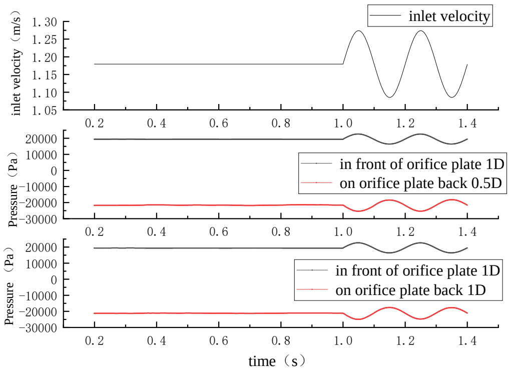


Figure 5 Orifice flowmeter front 1.5D and back 0.5D、1D pressure change

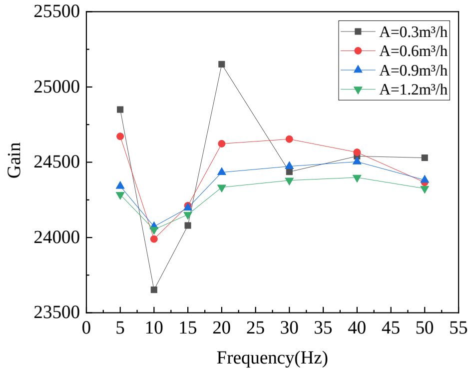
As can be seen from Figure 4 that when the orifice flowmeter is given a sinusoidal pulse velocity, the pressure change of the orifice flowmeter output is the same as that of the sinusoidal signal, but the amplitude change is relatively different. The pressure of orifice flowmeter changes inversely with the change of sinusoidal signal.Therefor, when the input velocity increases, the pressure in front of the orifice flowmeter increases and the pressure back of the orifice flowmeter decreases, forming two opposite sinusoidal signals.

3. Dynamic characteristics analysis of sinusoidal pulsating flow response of orifice flowmeter

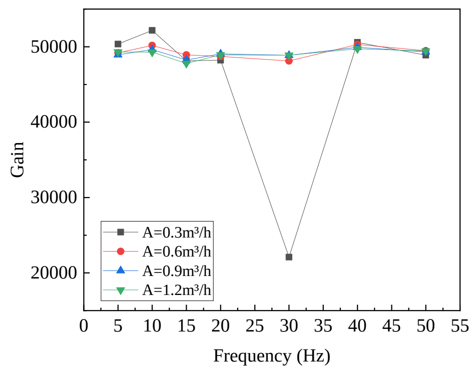
The dynamic characteristics of the orifice flowmeter under sinusoidal pulsating flow, mainly including amplitude-frequency characteristics and phase-frequency characteristics. The amplitude-frequency characteristic refers to the ratio of the output signal amplitude to the input signal amplitude. The phase-frequency characteristics refers to the difference between the phase of the input signal and the output signal. The amplitude-frequency characteristics and phase-frequency characteristics of the orifice flowmeter under pulsating flow are analyzed in this paper.

3.1 Amplitude-frequency characterization of sinusoidal pulsating flow response

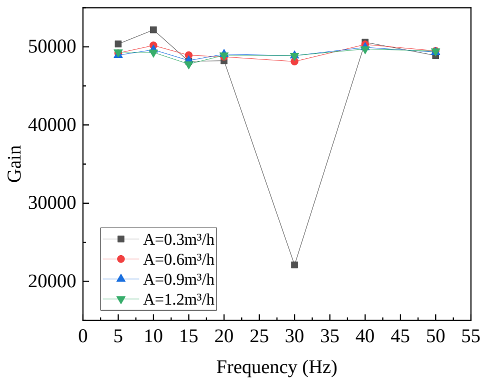
By processing the simulation data, the ratio of the output amplitude to the upper input amplitude value (i.e., gain) is plotted as a line graph with frequency, as shown in Figure 6(A is an abbreviation of the Amplitude). In Figure6(a)-Figure6(f) show the variation of gain with frequency for different throttling ratio and different flow rate.



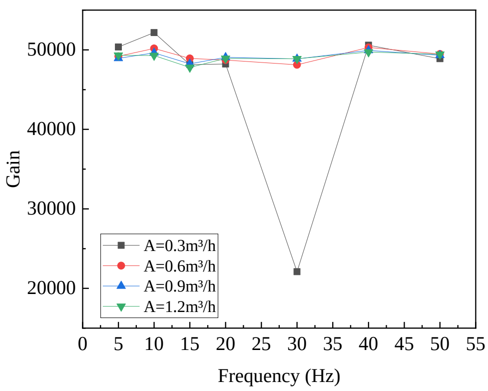
(a) β=0.2,flow rate=3m³/h



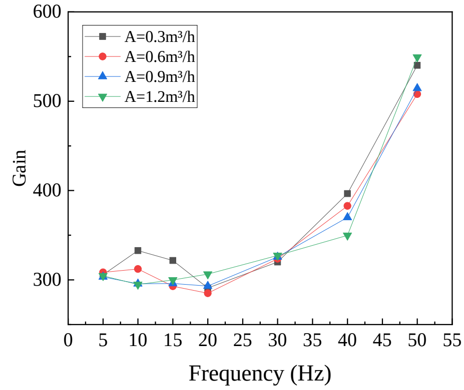
(b) β=0.2, flow rate =6m³/h



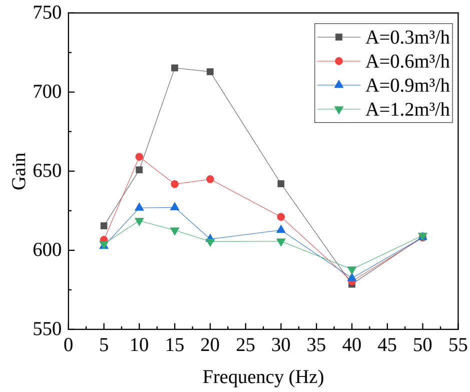
(c) β=0.4, flow rate =3m³/h



(d) β=0.4, flow rate =6m³/h



(e) β=0.6, flow rate =3m³/h



(f) β=0.6, flow rate =6m³/h

Figure 6 Amplitude-frequency characteristics of different throttling ratios and flow rate

As shown in Figure 6:

(1) The amplitude-frequency characteristics of the flow rate of 6 m³/h are better than those of 3 m³/h when the throttling ratio is 0.2. The amplitude-frequency characteristics of the flow rate of 3 m³/h is better than those of 6 m³/h when the throttling ratio is 0.4 or 0.6.

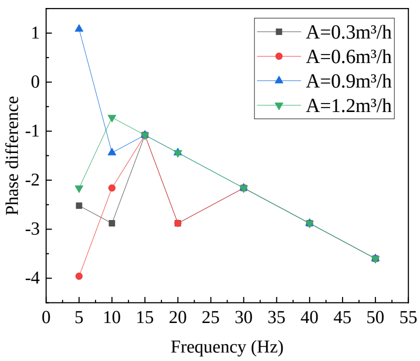
(2) With the same throttling ratio, the amplitude-frequency characteristics of different flow rate have different trends and different stability. It can be seen that the stability of the gain is mainly related to the working conditions .

(3) Through the Figure6(a)-Figure6(f), it can be seen that the gain varies more with frequency when the amplitude is 5. When the amplitude in the range of 0.6m³ /h to 1.2m³ /h, the gain is stable and does not change with the frequency.

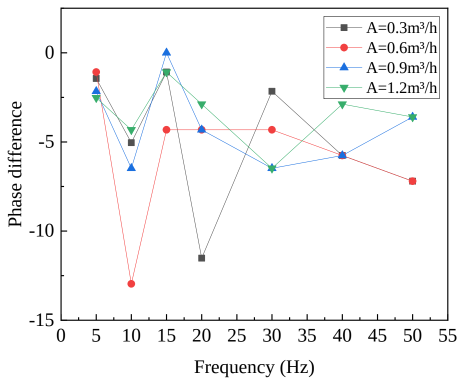
(4) When the throttling ratio is 0.2, the flow rate is 6m³/h, and the amplitude in the range of 0.6m³ /h to 1.2m³ /h, the linearity error is 1.9860% at the minimum.

3.2 Phase frequency characterization of sinusoidal pulsating flow response

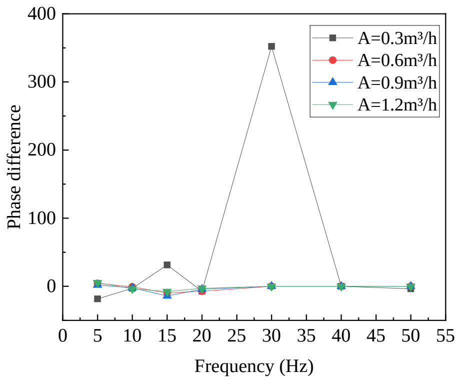
By processing the simulation data, plot the phase difference with frequency(The phase difference is the difference between the input signal and the output signal)as shown in Figure 7. In Figure7(a)-Figure7(f) show the variation of phase difference with frequency at different throttling ratio and different flow rate.



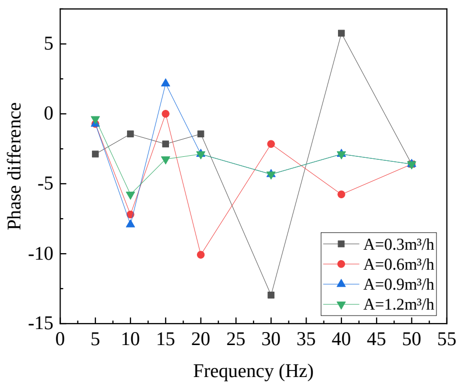
(a) β=0.2, flow rate =3m³/h



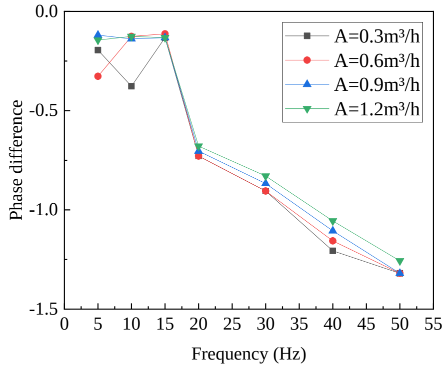
(b) β=0.2, flow rate =6m³/h



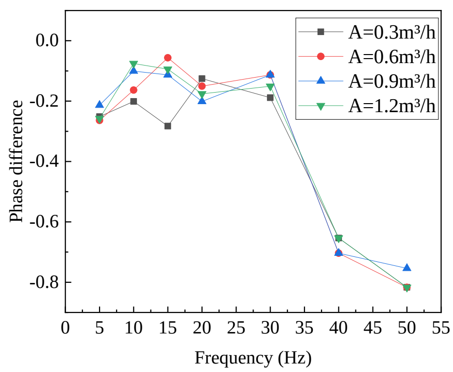
(c) β=0.4, flow rate =3m³/h



(d) β=0.4, flow rate =6m³/h



(e) β=0.6, flow rate =3m³/h



(f) β=0.6, flow rate =6m³/h

Figure 7 Phase-frequency characteristics of different throttling ratio and flow rate

As shown in Figure 7:

(1) The phase-frequency characteristics of flow rate 6m³/h are better than those of flow rate 3m³/h when the throttling ratio is 0.2. When the throttling ratio is 0.4 or 0.6, the change of phase-frequency characteristics with the flow rate is not obvious.

(2) At the same throttling ratio, the change of flow rate has less effect on the stability of phase-frequency characteristics. The change of throttling ratio has more influence on the stability of phase-frequency characteristics. But when the amplitude in the range of

$0.9m^3/h$ to $1.2m^3/h$, the phase-frequency characteristics are relatively stable.

(3) When the throttling ratio is 0.2, the flow rate is $6m^3/h$ and the amplitude is $0.3m^3/h$, the phase difference reaches a maximum of 359.28 degrees. When the amplitude is greater than $0.3m^3/h$, the phase difference is smaller, the minimum is -7.56° .

4. Conclusions

In this paper, the dynamic characteristics of the orifice flowmeter are analyzed by CFD simulation technique. The dynamic characteristics of the orifice flowmeter under sinusoidal pulsating flow is studied for different structures and different flow rate. The following conclusions are drawn:

(1) The dynamic characteristics of the orifice flowmeter and the throttling ratio is irrelevant, the change of the throttling ratio does not affect the stability of the dynamic characteristics, will only affect the size of the gain and phase difference.

(2) When the amplitude in the range of $0.6m^3/h$ to $1.2m^3/h$,orifice flowmeter has a better amplitude-frequency characteristics. When the amplitude is in the range of $0.9m^3/h$ to $1.2m^3/h$, orifice flowmeter has a better phase-frequency characteristics. It can be seen that when the amplitude is larger, the dynamic characteristics of the orifice flowmeter is more stable.

(3) When the throttling ratio is 0.2, the flow rate is $6(m^3/h)$, and the amplitude is $1.2m^3/h$ the minimum linearity of amplitude-frequency characteristics is 1.9860% and the minimum phase difference is -7.56°.

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