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Research on double differential pressure dynamic flowmeter①

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Abstract

When testing an electrohydraulic proportional valve, it is necessary to test the high frequency dynamic flow with bias. Because of the limitation of the piston stroke, a no-load hydraulic cylinder is only suitable for a reciprocating symmetrical dynamic flow test. Since the traditional differential pressure flowmeter is affected by viscosity and inertia of the fluid, it is only suitable for measuring steady flow. Therefore, a new type of double pressure differential dynamic flowmeter is designed to improve the traditional differential pressure flowmeter. The influence of fluid viscosity and inertia in the flow process are negated by subtracting the differential pressure in section expansion from the differential pressure in section contraction. The double differential pressure flowmeter is modeled and a flow meter prototype is designed. Then, the flow coefficients are identified and corrected by a practical test. Finally, the dynamic performance and steady-state precision of the flowmeter are verified by comparing with the test results of the no-load hydraulic cylinder. The double differential pressure dynamic flowmeter is proven to measure dynamic flow accurately, especially at higher dynamic frequencies.

Key words: dynamic flowmeter, double differential pressure, contrast experiment, coefficient correction

0 Introduction

Flow is one of the most important parameters in the field of fluid power transmission. With the innovation and development of electrohydraulic control technology since 1970s and 1980s, the testing of the dynamic and static characteristics of both electrohydraulic servo valves and proportional valves have become more and more important. The dynamic flow test is an important method of evaluating the performance of electrohydraulic servo valves and proportional valves. However, due to the complexity of the fluid itself, especially the viscosity and inertia effect in the state of dynamic flow combining with the influence of moving parts of the flowmeter, it is difficult to measure the dynamic flow[1].

In the 1990s, Ohio State University in the United States proposed an approach to determine the instantaneous flow rate by testing the pressure at both ends of the tube, based on the pipeline dynamic model[2]. In recent years, Ref. [3] has conducted relevant research on micro flowmeters based on capacitance, which is capable of accurately measuring the fluid flow at low Reynolds number. In addition, Ref. [4] studied the Coriolis mass flowmeter in depth and proposed a measurement method based on the dynamic model of a mass flowmeter. Rodrigues and Furlan[5] has developed a micro sensor with superior dynamic characteristics based on microelectro mechanical systems, which can be used to measure the flow of gas and liquid.

In the domestic study of dynamic flow measurements, earlier study was a type of 2-way plug-in dynamic flowmeter designed by Zhejiang University. The study used a valve core as a measuring element with specially designed valve port and the size of the flow was measured indirectly using the displacement of the valve core[6]. In addition, South China University of Technology has designed a 2-way intelligent differential pressure type flowmeter based on similar principles as Zhejiang University. When the fluid flows through the cavity, the spool shifts with the annular throttling area

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between the shell beginning to form, and the pressure difference is generated under the action of the oil flow. Then, the spool is balanced by the forces of pressure difference and spring. Therefore, the flow rate can be calculated by measuring the displacement of the spool[7]. The new plug-in double V-type flowmeter designed by Ningxia polytechnic College combines the advantages of Verabar flowmeter and Venturi tube in structure. It has the advantages of large output difference pressure, small pressure loss and wide measuring range. However, the measurement dynamic flow accuracy is not high, and its processing on the mathematical model is too simple[8,9]. Compared with the methods mentioned above, Yanshan University has introduced the concept of soft measurement into the flow measurement. Based on the basic structure of a differential pressure flowmeter, the calculation formula for dynamic flow measurement is established by analyzing the hydrodynamic model under laminar flow conditions[10]. Recently, Yanshan University has also designed a new type of dynamic flowmeter, which connects the no-load hydraulic cylinder and the servo motor driven metering pump in parallel. The no-load hydraulic cylinder mainly measures the high frequency part of the flow, the metering pump measures the low frequency part of the flow, finally the two flows are added to obtain the dynamic flow[11,12]. Anhui University of Science and Technology designed a planetary gear flowmeter and deduced a method of calculating the coefficients of meshing displacement of planetary gear. Then, the results are applied to optimizing the structure and obtaining the dynamic flow measurements by reducing the flow pulsation[13-15].

Among all these studies, the differential pressure flowmeter has the advantage of quick response. However, since the differential pressure is easily influenced by the fluid inertia and flow state, it is difficult to establish a very precise and reliable mathematical model that can achieve measurements with high accuracy. The rotor part of the rotameter flowmeter is mainly inertial component. Thanks to the compensation methods of computers and improvement of the flowmeter structure, the accuracy has been improved obviously, but inertia influence has not been solved fundamentally. The no-load hydraulic cylinder applied to test the servo valve has the advantages of good dynamic characteristics and high accuracy. However it is limited by the range of the effective stroke of the piston, so it cannot be used to measure unidirectional continuous flow.

1 Principle of double differential pressure dynamic flowmeter

1.1 Design of measuring tube

As shown in Fig. 1, the measuring tube in a double differential pressure dynamic flowmeter has been improved using the basic structure of a conventional differential pressure flowmeter as follows. First, entire length is extended to make the flow state more stable. Then, three pressure measurement points have been devised in cross sections, Ⅰ, Ⅱ and Ⅲ. Finally, the entire structure is symmetrical, making it easier to measure the positive direction flowrate as well as the opposite direction flowrate.

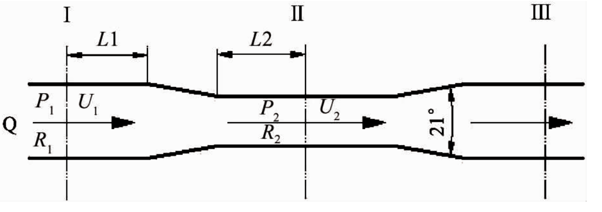


Fig. 1 Measuring tube structure

1.2 Mathematical model

In Fig. 1, the diameter of cross section Ⅰ and section Ⅲ is R_1, the diameter of cross section Ⅱ is R_2, and the corresponding axial velocity is u_1 and u_2. The flow is assumed to be axisymmetric and incompressible laminar with a straight-line streamline in the 3 sections of the tube. The pipe is placed horizontally so the axis coincides with the z-axis. Then the axial cylindrical coordinate system is established.

The fluid flowing in the measuring tube is laminar flow: the radial velocity is $v \equiv 0$; the axial velocity u is a function of R: $u = f_1(R)$; ignoring the compressibility of the oil, pressure P is a function of axial coordinate z: $P = f_2(z)$.

By simplifying the N-S equations of the z-component in the cylindrical coordinate system, the laminar differential equation of circular pipe is obtained:

$$\frac{\partial v_z}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + v\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) \tag{1}$$

In the above equations, ρ is fluid density, v is fluid kinematic viscosity coefficient.

Multiplying the both sides by $2\pi r$ and integrating from $r = 0$ to $r = R$ respectively, the following formula is obtained:

$$\frac{\partial q}{\partial t} = -\frac{\pi r^2}{\rho}\frac{\partial p}{\partial z} - 8\pi v\bar{u} \tag{2}$$

where $\bar{u}$ is the mean velocity at the cross section.

For tubes with equal diameters: $\frac{\partial p}{\partial z} = \frac{\Delta p}{l}$, substituting this into the formula above, the following formula is obtained:

$$\Delta p = \frac{l\rho}{A}\frac{\partial q}{\partial t} + \frac{8\pi v \rho l \bar{u}}{A} \tag{3}$$

In the conical reducing section and the conical diffusing section of the measuring tube, changes in velocity and kinetic energy will cause additional pressure changes as well as the loss of local resistances.

In the conical reducing section:

$$\Delta p_{in} = \Delta p_B + \Delta p_{il} = \frac{\rho}{2}(\sigma^4 - 1)\bar{u} + \frac{\rho\bar{u}}{2}\zeta_1 \tag{4}$$

In the conical diffusing section:

$$\Delta p_{out} = \Delta p_B + \Delta p_{ol} = \frac{\rho}{2}(\sigma^4 - 1)\bar{u} + \frac{\rho\bar{u}}{2}\zeta_2 \tag{5}$$

In the above equations, Δp_B is bernoulli effect, Δp_{il} is entrance loss, ζ is local resistance coefficient, Δp_{ol} is export local loss, σ is radius ratio $\sigma = D_1/D_2$.

Thus, the pressure drop from section Ⅰ to section Ⅱ consists of 3 parts: the pressure drop of equal diameter tubes in length l_1; the pressure drop of the conical reducing section; and the pressure drop in length l_2:

$$\Delta p_{1-2} = \rho\left(\frac{l_1}{A_1} + \frac{l_2}{A_2}\right)\frac{\partial q}{\partial t} + \rho(l_1 + l_2\sigma^4)\frac{8v\bar{u}_1^2}{R_1^2} + \frac{\rho}{2}(\sigma^4 - 1)\bar{u}_1^2 + \frac{\rho\bar{u}_1^2}{2}\zeta_1 \tag{6}$$

Therefore, the pressure drop from section Ⅱ to section Ⅲ also consists of 3 parts:

$$\Delta p_{2-3} = \rho\left(\frac{l_1}{A_1} + \frac{l_2}{A_2}\right)\frac{\partial q}{\partial t} + \rho(l_1 + l_2\sigma^4)\frac{8v\bar{u}_1^2}{R_1^2} + \frac{\rho}{2}(\sigma^4 - 1)\bar{u}_1^2 + \frac{\rho\bar{u}_1^2}{2}\zeta_2 \tag{7}$$

Subtracting the 2 sides of Eqs(6,7) at the same time:

$$\Delta p_{1-2} - \Delta p_{2-3} = \rho(\sigma^4 - 1)\bar{u}_1^2 + \frac{\rho\bar{u}_1^2}{2}(\zeta_1 - \zeta_2) \tag{8}$$

In Eq. (8), the inertia term and the viscosity term from Eq. (6) and Eq. (7) are canceled out, which reduces the influence of fluid viscosity and inertia in the dynamic flow measurement. The mathematical model of the flow rate is simple and easy. If 2 differential pressure sensors are used to measure the pressure difference between sections Ⅰ-Ⅱ and sections Ⅱ-Ⅲ, the flow of the measuring tube can be calculated with the following formula:

$$q = A_1\bar{u}_1 = \frac{\pi D_1^2}{4}\sqrt{\frac{\Delta p_{1-2} - \Delta p_{2-3}}{\rho\{(\sigma^4 - 1) + \frac{1}{2}(\zeta_1 - \zeta_2)\}}}$$

$$= C_d A_1 \sqrt{\frac{\Delta p_{1-2} - \Delta p_{2-3}}{\rho(\sigma^4 - 1)}} \tag{9}$$

where, C_d is a constant related to the structure of the measuring tube and the fluid characteristics.

$$C_d = \sqrt{\frac{(\sigma^4 - 1)}{(\sigma^4 - 1) + \frac{1}{2}(\zeta_1 - \zeta_2)}}$$

The local resistance coefficient ζ is related to the structure of the measuring tube and can be measured experimentally.

Although Eq. (9) is derived under steady-state incompressible laminar flow conditions, when pressure changing in the pipe is low and the volume between the cross sections of the measuring tube in Fig. 1 is relatively small, the compressibility of the fluid is almost-negligible. Therefore, the flow rate derived from the double pressure difference is general. For example, the distance between section Ⅰ and Ⅲ in Fig. 1 is L = 200 mm, the pressure wave is transmitted at the speed of sound, v = 340 m/s, and the transfer time of the pressure wave is $\Delta t = 5.9 \times 10^{-4}$ s. When the frequency of the flow does not change significantly, the influence of fluid compression on flow can be neglected[16].

2 Design of flowmeter structure

The main structure of the flowmeter consists of a horizontal measuring tube and 2 differential pressure sensors, as shown in Fig. 2. Inside the measuring tube, the internal diameter changes from large to small and from small to large again, R_1 = 14 mm, R_2 = 7 mm and the angle of reduction and diffusion is 21°. The tube can be divided into 5 segments: a left large section, a conical reducing section, a middle small section, a conical diffusing section and a right large section. In the middle position of each left large section, the middle small section, and the right large section, there are 4 openings that are radially symmetric, and the pressure rings used to measure are welded to connect the pressure difference sensor, as shown in Fig. 2.

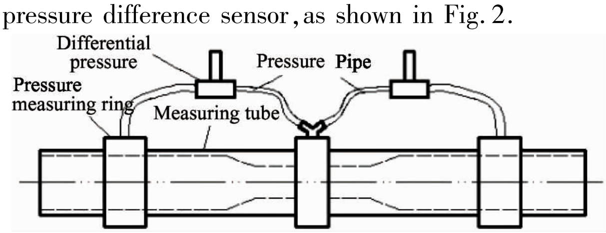


Fig. 2 Flow meter body structure

The measurement process of the double differential dynamic flowmeter includes collecting the voltage signal of the differential pressure sensor, signal processing and conversion, data calculation and output display. The hardware system is shown in Fig. 3.

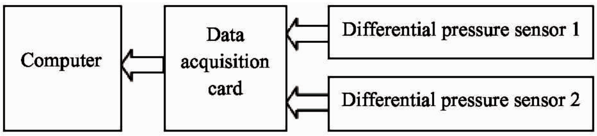


Fig. 3 Flow meter test system hardware structure

The double pressure dynamic flow test program is developed in LabVIEW. The data acquisition card is driven to obtain the signal of the 2 differential pressure sensors. Simultaneously, it can also be driven to process data and calculate the instantaneous flow rate according to the mathematical model[17]. The specific programming results are shown in Fig. 4 and Fig. 5.

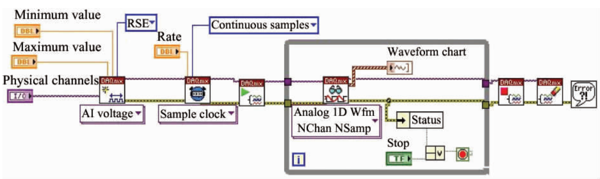


Fig. 4 Analog signal acquisition subroutine

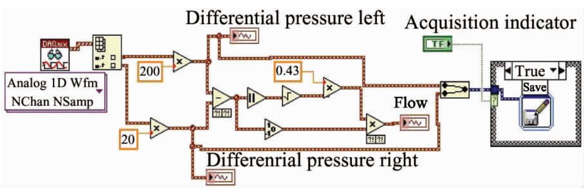


Fig. 5 Instantaneous flow calculation subroutine

3 Design of experiment system and preliminary calibration of parameters

To test the dynamic double differential pressure flowmeter, a contrast experiment with a dynamic flow test is designed. Different types of dynamic flow are produced by controlling the servo valve, and the double differential pressure flowmeter and no-load hydraulic cylinder are used to measure the flow rate at the same time. Under the same experimental conditions, the dynamic flowmeter is compared with the no-load cylinder to verify and evaluate its accuracy and dynamic performance[18].

The experimental system is shown in Fig. 4. The oil source includes a gear pump, a relief valve and a filter. The testing part consists of the electrohydraulic servo valve, the no-load cylinder and the dynamic flowmeter. The entire experimental system is shown in Fig. 6, and the principle of the hydraulic system is shown in Fig. 7.

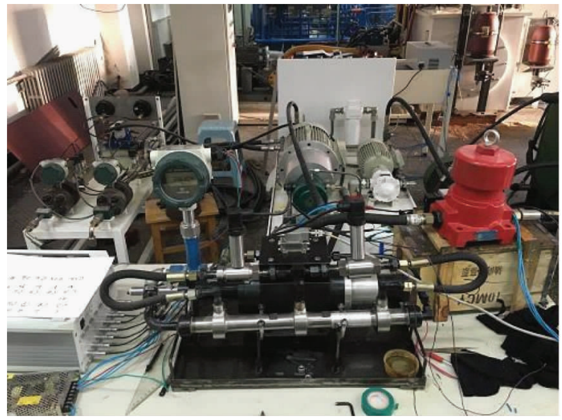


Fig. 6 Comparison test system

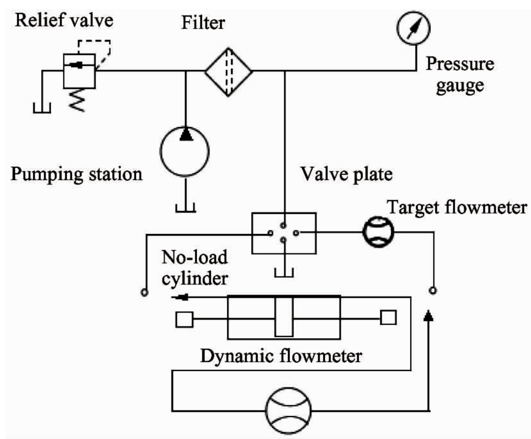
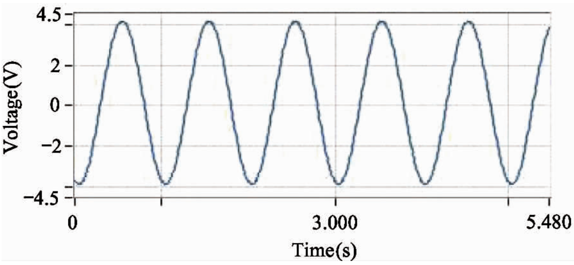


Fig. 7 Schematic diagram of comparative experimental system

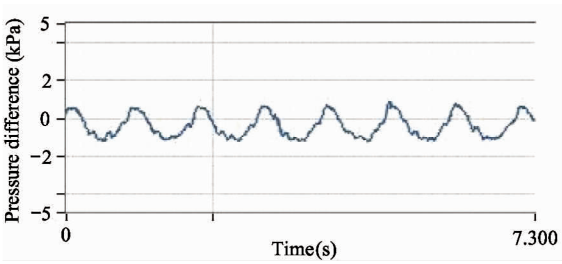
To determine the local resistance coefficient, a target flowmeter has been connected in series with the dynamic double differential pressure flowmeter in the experimental system. The controlling voltage of the electrohydraulic servo valve is changed slowly from 1 V to 5 V to produce similarly slow variations in flow. Then, the measured results of both the target flowmeter and the double differential pressure values of the new flowmeter are read and saved, and substituted into Eq. (9) to obtain the local resistance coefficients of the measuring tube, $\zeta_1 = 0.4714$, $\zeta_2 = 0.0287$, $C_d = 0.9927$.

4 Experimental results and analysis

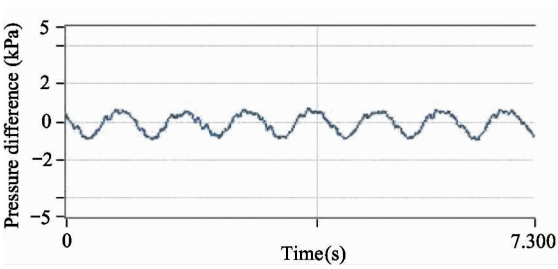
The results of the comparison test using a sine signal with a frequency of 1 Hz are shown in Fig. 8, where Fig. 8(a) is the measured voltage signal, Fig. 8(b) is the differential pressure signal measured by the left differential pressure sensor, Fig. 8(c) is the differential pressure signal measured by the right differential pressure sensor, Fig. 8(d) is the flow rate signal measured by the unloaded hydraulic cylinder, and Fig. 8(e) is the flow signal measured by the double differential pressure dynamic flowmeter.



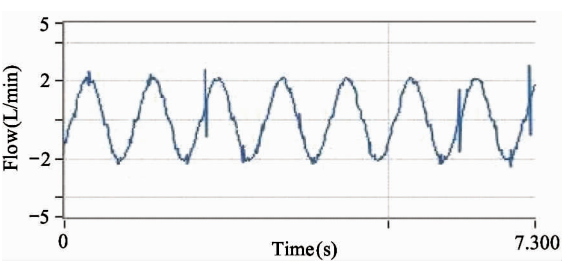
(a) The measured voltage signal



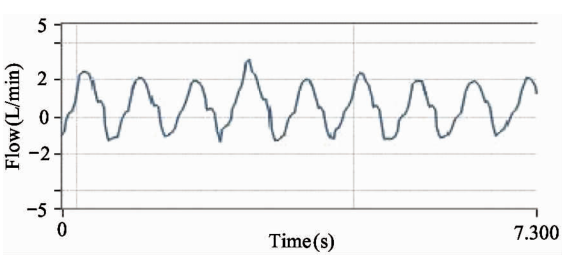
(b) The differential pressure signal measured by the left differential pressure sensor



(c) The differential pressure signal measured by the right differential pressure sensor



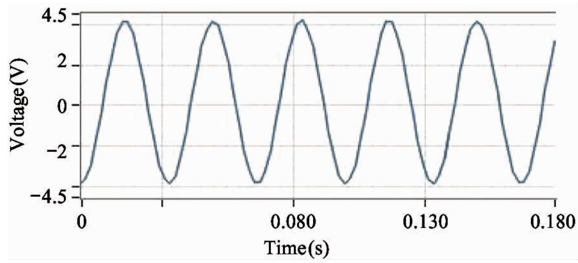
(d) The flow rate signal measured by the unloaded hydraulic cylinder



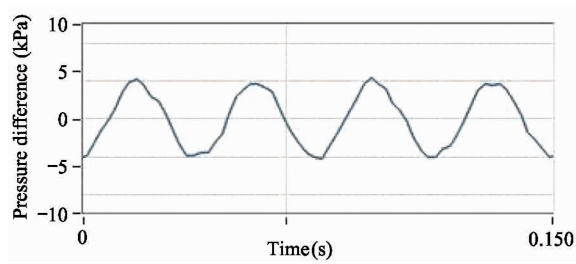
(e) The flow signal measured by the double differential pressure dynamic flowmeter

Fig. 8 Sinusoidal signal (1Hz) test waveform

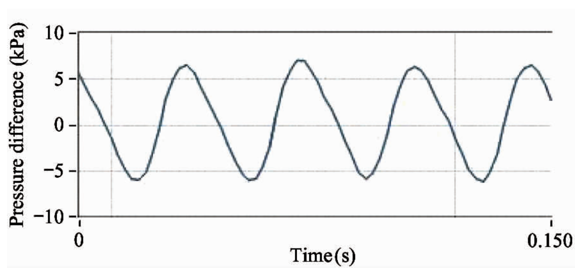
The results of the contrast test for sinusoidal signals with a frequency of 30 Hz are shown in Fig. 9, where Fig. 9(a) is the measured control voltage signal, Fig. 9(b) is the differential pressure signal measured



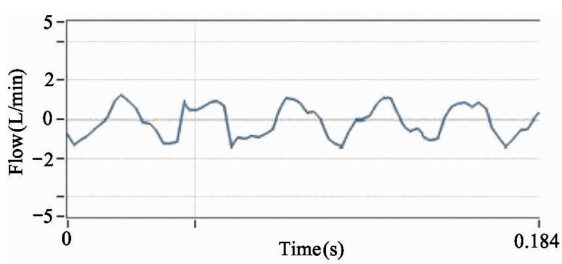
(a) The measured control voltage signal



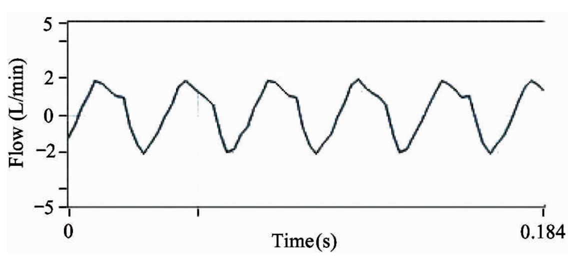
(b) The differential pressure signal measured by the left differential pressure sensor



(c) The differential pressure signal measured at the right side of the differential pressure sensor



(d) The measured flow signal of the no-load hydraulic cylinder



(e) The flow signal measured by the double pressure differential dynamic flowmeter

Fig. 9 Sinusoidal signal (30 Hz) test waveform by the left differential pressure sensor, Fig. 9(c) is the differential pressure signal measured at the right side of the differential pressure sensor, Fig. 9(d) is the measured flow signal of the no-load hydraulic cylinder, and Fig. 9(e) is the flow signal measured by the double pressure differential dynamic flowmeter.

The results of the comparison test for a sinusoidal signal with a frequency of 50 Hz is shown in Fig. 10, where Fig. 10(a) is the measured control voltage signal, Fig. 10(b) is the differential pressure signal measured by the left differential pressure sensor, Fig. 10(c) is the differential pressure signal measured by the right differential pressure sensor, Fig. 10(d) is the flow signal measured by the unloaded hydraulic cylinder, and Fig. 10(e) is the flow signal measured by the double differential pressure dynamic flowmeter.

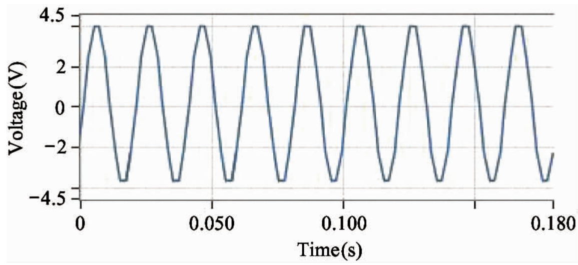
From the test results with sine signals with different frequencies, the double pressure differential dynamic flowmeter is consistent with the no-load hydraulic cylinder with some deviation. When the frequency of a given sinusoidal signal is less than 30 Hz, the flow signal measured by the no-load cylinder is smoother than that of the double differential dynamic flowmeter. As the frequency of the sinusoidal signal increases, the flow signals measured by the no-load cylinder are gradually unstable, while the signals measured by the double differential dynamic flowmeter tend to be smoother. When the fluctuation frequency of flow reaches 50 Hz, the flow signal measured by the no-load cylinder is unstable, but the flow signal measured by the double differential pressure flowmeter is still clear and accurate.

5 Model correction

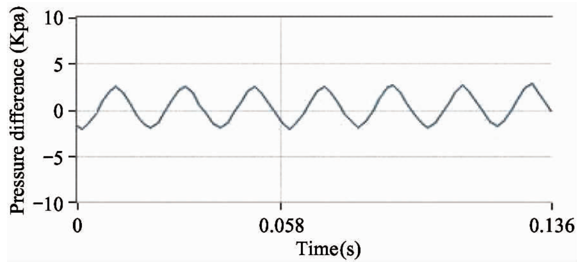
The experimental data shows that there is some deviation in the measurement results of the double differential pressure flowmeter and the no-load hydraulic cylinder. The error could be caused by changes in the experimental conditions, the elasticity of oil, and the limitations of the mathematical model based on laminar flow assumption[19].

Therefore, a correction term K is introduced into the calculation formula of the flow rate of the double pressure differential dynamic flowmeter. The corrected flow rate formula is as follows:

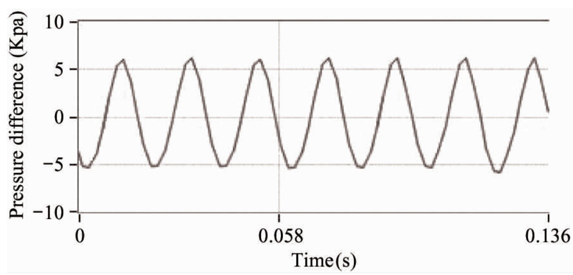
$$q = K\pi R_1^2 \sqrt{\frac{\Delta p_{1-2} - \Delta p_{2-3}}{\rho\left\{(\sigma^4 - 1) + \frac{1}{2}(\zeta_1 - \zeta_2)\right\}}} \quad (10)$$



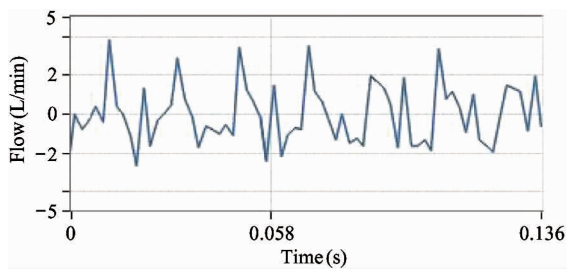
(a) The measured control voltage signal



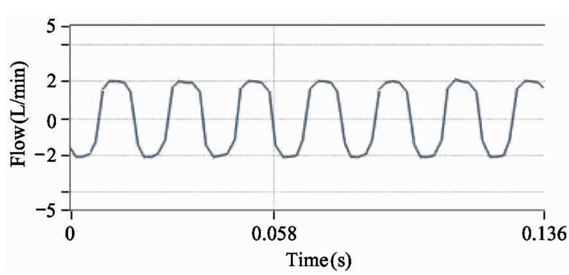
(b) The differential pressure signal measured by the left differential pressure sensor



(c) The differential pressure signal measured by the right differential pressure sensor



(d) The flow signal measured by the unloaded hydraulic cylinder

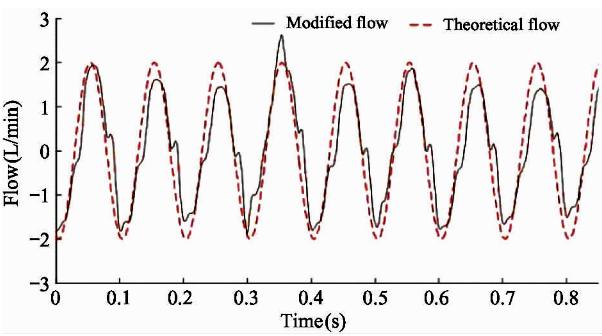


(e) The flow signal measured by the double differential pressure dynamic flowmeter

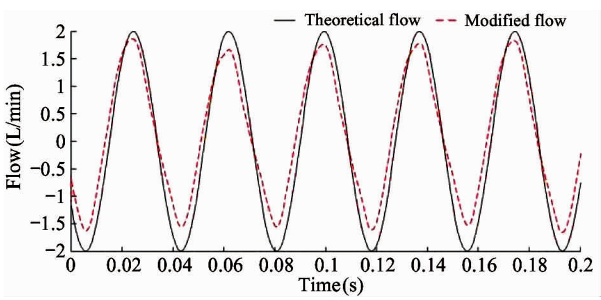
Fig. 10 Sinusoidal signal (50 Hz) test waveform

Through a large number of experimental analysis and comparisons, the mathematical model of the correction term can be determined: $K = \frac{\alpha}{e^{\frac{f}{\beta}}} + 1$, α and β are unknown parameters in the model, where α is related to the structure of the throttling device and the oil density and f is the main frequency of the flow signal[20]. Applying the least squares method to determine the parameters: $\alpha = 1.031$, $\beta = 10$; and the correction term is $K = \frac{1.031}{e^{\frac{f}{10}}} + 1$.

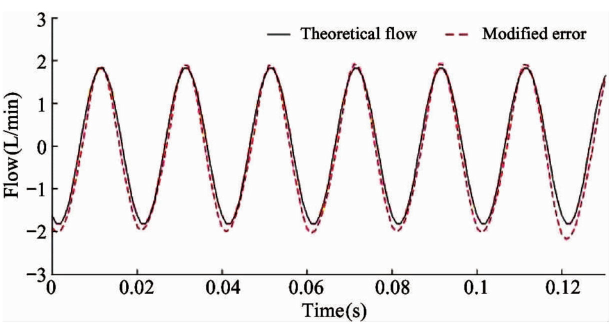
The corrected test data are shown in Fig. 11, where Fig. 11(a), Fig. 11(b) and Fig. 11(c) are the flow data at 10 Hz, 30 Hz, 50 Hz, respectively. As shown in Fig. 11, the corrected flow is obviously more accurate, and the error decreases gradually with the increase of frequency.



(a) Flow data at 10 Hz



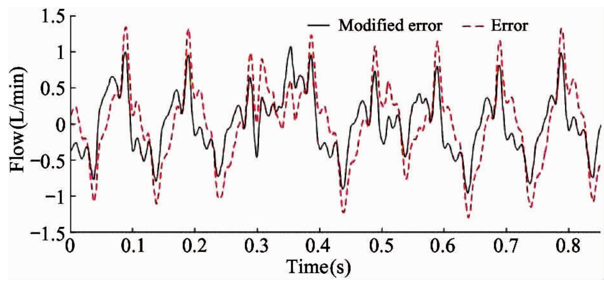
(b) Flow data at 30 Hz



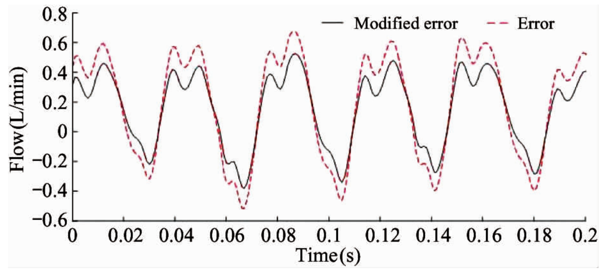
(c) Flow data at 50 Hz

Fig. 11 Corrected measured flow rate

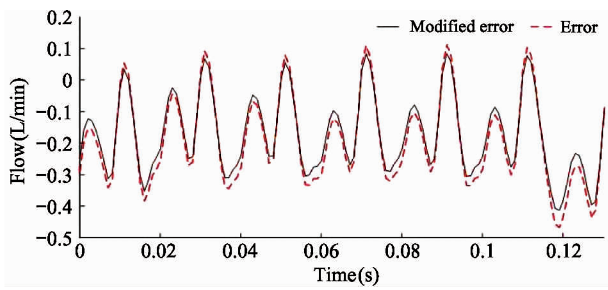
The measurement errors before and after model correction are shown in Fig. 12, where Fig. 12(a), Fig. 12(b) and Fig. 12(c) are the measurement error at 10 Hz, 30 Hz, 50 Hz, respectively. From the figure, the flow measurement error is obviously reduced by updating the model.



(a) Measurement error at 10 Hz



(b) Measurement error at 30 Hz



(c) Measurement error at 50 Hz

Fig. 12 Corrected before and after the error

6 Conclusions

The idea of using double differential subtraction to negate the effect of fluid viscosity and inertia is proposed. The dynamic double differential pressure flowmeter was designed and a mathematical model is established.

The model parameters are determined experimentally. Using the contrast test with the no-load hydraulic cylinder, the accuracy of the dynamic flow measurement of the double pressure differential dynamic flowmeter is verified.

The double pressure differential dynamic flowmeter has the advantages of low damping and no inertial component, which improve the dynamic characteristics substantially. In addition, the flowmeter is not limited by stroke and is suitable for the measurement of various complicated flows and micro instantaneous flow. Apart from replacing the no-load hydraulic cylinder to carry out the flow test of electrohydraulic servo valves, it can also be applied to dynamic tests of an electrohydraulic proportional flow valve.

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