Research on Closed-Loop Control and Flow Noise for Piezoelectric Type Micro Flow Controller for Electric Propulsion

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Abstract. For the control problem of micro-flow controller using piezoelectric ceramics as driving components in the electric propulsion system, we directly utilize the collected rate of flow as the state and give a closed-loop control method which can eliminate the hysteresis and creep characteristics of piezoelectric ceramic. Through the experiment with the real flow control system, it is verified that the control method can effectively stabilize and follow the rate of flow, and the influence of ambient temperature on the closed-loop flow control is analysed. Then by analysing the power spectral density analysis of the obtained flow data, the flow noise is significant in the low frequency band for different closed-loop target flows, while in order to reduce the flow noise, the flow sampling frequency should be increased.

Keywords: Piezoelectric ceramics · flow control · closed-loop control · noise influence · power spectral density

1 Introduction

The micro flow controller is an important component of the electric propulsion system, which is used to regulate the flow of propellant and realize accurate distribution, ensuring the long-life and high reliability of the electric propulsion system [1]. With the increase of various scientific detection, more requirements are put forward for the micro flow controller, including continuous regulation in a large flow range, high precision, steady output, fast response and other adjustment characteristics. Therefore, it is very important to find an effective and reliable control method of the micro flow controller to meet the high-precision flow regulation.

Currently, the control method of micro flow controller used in electric propulsion system include the direct and the indirect flow control methods [2, 3]. In the indirect flow control method, the fixed structure throttling micro flow control method regulates the flow by adjusting the aperture and pressure that affect the flow. The metal capillary, the throttle orifice and the metal cellular materials are usually used as the throttling structure [4–7], which has the advantages of simple structure and low development

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difficulty, but needs to carry out ground calibration in advance and take the calibration value as the basis for the flow regulation of space electric propulsion system, the response speed of flow regulation is slow and the accuracy is low. Another indirect flow control method uses the exciting current to deform the giant magnetostrictive material to realize flow regulation [8]. Company Moog of the United States has developed 51E339 giant magnetostrictive proportional flow control valve, which uses the anode current of electric thruster as the collected signal for flow control [9–11]. It can meet the requirements of large-scale flow regulation and high-precision control, but considering the control of cathode flow, it is necessary to set a flow distributor downstream. Therefore, the giant magnetostrictive flow control valve is only equivalent to the pressure reducer in the flow control system. The direct flow control method directly uses the collected flow as the control state. The piezoelectric flow control valve is a controller adopting the direct flow control method, which uses the inverse piezoelectric effect of the piezoelectric material to drive the valve to realize the flow regulation, has the characteristic of high precision and large-scale flow regulation. The British Marotta company has developed a piezoelectric proportional flow control valve with a flow range of 0–25 mg/s for ROS 2000 and T6 ion electric thrusters [12], AAS-I company of Italy has developed a piezoelectric flow proportional control valve that can work within the temperature range of −30 °C–+50 °C [8], VACCO company of Canada has developed a high-precision piezoelectric control valve for vacuum environment [13].

In this paper, the control problem of micro flow controller for electric propulsion using the piezoelectric material as driving assembly is studied. The piezoelectric material, especially the controller using the piezoelectric ceramic as the actuator, has the characteristic of high displacement output precision. However, it also has the hysteresis characteristic making the displacement difference exist between the opening pressure and the reducing pressure curves, and the creep characteristic making the displacement of the piezoelectric ceramic continue to vary slowly after reaching a certain value [14, 15]. These characteristics bring difficulties to achieve precise control and rapidly stabilize the flow. Therefore, the closed-loop control method that directly uses the collected flow as the control variable in this paper to make the flow quickly reach the target flow and remain stable, so as to eliminate the effect of creep and hysteresis of piezoelectric drive assembly.

This paper aims at the control problem of piezoelectric micro flow controller used in electric propulsion system, the closed-loop control model of the flow controller is given first, then the control method is introduced into the real flow control system to verify the reliability of the closed-loop control method. The effect of temperature on flow closed-loop control is analysed through experiments under different ambient temperature conditions, and the effect of flow noise of this control method is analysed by power spectral density of flow.

2 Control Model of Micro Flow Controller

As shown in Fig. 1, the micro flow controller is composed of armature assembly, seal assembly, piezoelectric driving assembly, etc. The main structure of the piezoelectric driving assembly is the piezoelectric ceramic. By controlling the voltage applied to

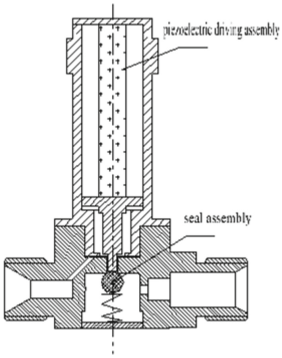

Fig. 1. The micro flow controller assembly

the piezoelectric driving assembly, the valve opening of the micro flow controller can be adjusted to control the flow. Under the supercritical and the critical conditions, the calculation equation of flow is

$$\dot{m} = C_d f_1 P_i \sqrt{\frac{2k}{RT(k+1)}} \times (\frac{2}{k+1})^{\frac{1}{k-1}} \tag{1}$$

where, $\dot{m}$ is the mass flow through the valve, C_d is flow coefficient through the valve, f_1 is the area of the valve throttling, P_i is the inlet pressure, R is the universal gas constant, T is the absolute temperature of propellant flowing through the valve, k is the adiabatic exponent.

According to Eq. (1), the mass flow $\dot{m}$ passing through the valve is determined by C_d, T, P_i and f_1. When P_i and T are constant, $\dot{m}$ is determined by f_1, that the required flow can be obtained by adjusting the area of the valve throttling.

The relation between the valve opening with the valve throttling is

$$f_1 = \pi d a \delta \frac{1 + \frac{\delta}{2a}}{\sqrt{(\frac{d}{2})^2 + (a+\delta)^2}} \tag{2}$$

$$a = \sqrt{r^2 - (\frac{d}{2})^2} \tag{3}$$

where, δ is the valve opening, d is the aperture diameter of the valve seat, r is the radius of the sealed ball.

The relation between the valve opening and the control voltage can be expressed by a second-order damped vibration model, which can be given by

$$m\ddot{\delta}(t) + b\dot{\delta}(t) + k\delta(t) = k_v V(t) + h(t) \tag{4}$$

When the piezoelectric dynamic characteristics is ignored, Eq. (5) can be converted to

$$\delta(t) = k_v V(t) + h(t) + x_0 \tag{5}$$

where $h(t)$ is the hysteresis displacement of the piezoelectric driving assembly. Combine Eq. (1) to Eq. (5), the open loop flow control can be realized.

Since the piezoelectric driving assembly use piezoelectric ceramic as the driving mechanism, and piezoelectric ceramic have the characteristics of creep and hysteresis. It is difficult to use the open-loop control to control the valve opening to stabilize the flow. Especially in the high-precision flow control, it is necessary to eliminate the influence of creep and hysteresis on the valve opening. Therefore, the closed-loop control method on flow and voltage can be directly adopted, forming a new control rate with the current flow state fed back in real time to achieve the dynamic stability of the flow.

Using the PID control method, the feedback control rate on flow and voltage can be given as

$$\begin{aligned} V(t) = \frac{1}{C_{scale}} \Big\{ & k_p[m_d - m(t)] \\ & + k_i \int_0^t [m_d - m(t)]dt + k_d \frac{dm(t)}{dt} \Big\} \end{aligned} \tag{6}$$

where, C_{scale} is the normalized variable of voltage, k_p, k_i and k_d are PID parameters.

Discretize Eq. (6), the discrete form of the relation between flow and voltage can be given by

$$\begin{aligned} V(k) = \frac{1}{C_{scale}} \Big\{ & k_p[m_d - m(k)] \\ & + k_i \sum_{i=1}^{k} [m_d - m(k)]\Delta T \\ & + \frac{k_d}{\Delta T}[m(k) - m(k-1)] \Big\} \end{aligned} \tag{7}$$

where ΔT is a discrete-time period.

The flow-voltage PID control schematic diagram is shown in Fig. 2. Due to fluid viscosity, there is no sudden change in flow, so there is a delay link between the real flow and the calculated flow.

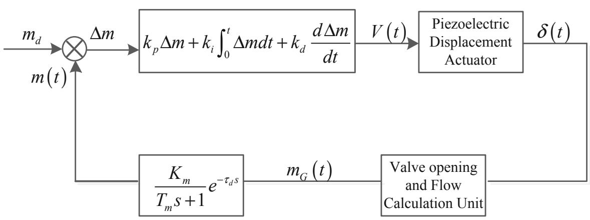

Fig. 2. Closed-loop control schematic diagram of flow controller

3 Results and Analysis

3.1 Closed-Loop Control Result of Micro Flow Controller

Assuming that the initial flow is 0 mg/s in the flow controller, we use the control rate shown in Eq. (7) to control the real micro flow control system. The control parameters are set to $k_i = 0.015$, $k_p = 0.105$ and $k_d = 0.001$. The period of flow control is 0.2 s, the parameters for the flow controller is given in Table 1. Setting the target flow is 3 mg/s, the ambient temperature 25 °C, the sampling frequency is 2.5 Hz, the flow-voltage curve when flow reaches steady is shown in Fig. 4. Setting the target flow is 0.2 mg/s, the ambient temperature 10 °C, the sampling frequency is 5 Hz, the flow-voltage curve when flow reaches steady is shown in Fig. 5.

It can be seen from Figs. 4 and 5 that under different sampling frequency, target flow and ambient temperature, the closed-loop control method with the control rate in Eq. (7) can make the flow of the piezoelectric micro flow controller climb to the target value and remain stable in a short time. While the control voltage will gradually decrease after the flow reaches steady-state, which is due to the influence of the creep characteristics of the piezoelectric ceramic, that is, the displacement of the piezoelectric ceramic will still increase slowly with time after it quickly reaches a certain value. Therefore, in order to keep the flow stable in the closed-loop control, it is necessary to reduce the driving voltage.

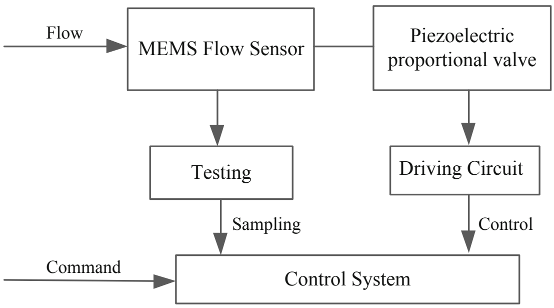

Fig. 3. Schematic diagram of flow controller closed loop control system

Table 1. The parameters for flow controller

Parameter	Value
discharge coefficient C_d	0.6
inlet pressure P_i	0.25 MPa
gas constant R	63.5 J/kgK
adiabatic exponent k	1.67
aperture diameter of the valve seat d	0.002 m
radius of the sealed ball r	0.002 m

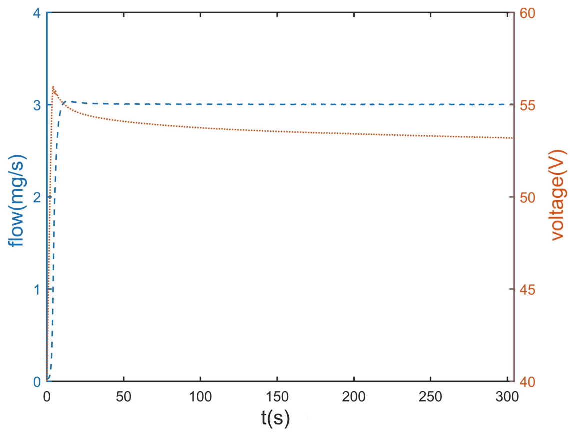

Fig. 4. The flow-voltage curve when flow reaches steady on the ambient temperature 25 °C and the sampling frequency is 2.5 Hz

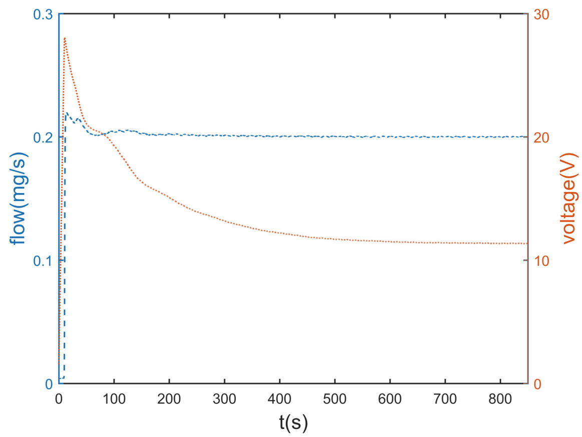

Fig. 5. The flow-voltage curve when flow reaches steady on the ambient temperature 10 °C and the sampling frequency is 5 Hz

Set the sampling frequency to 2.5 Hz, the target flow is gradually increased from 0 mg/s to 3 mg/s and then decreases, keep the flow stable at each target flow point for 30 s to observe the follow effect of the closed-loop control of the piezoelectricity micro flow controller on the changing flow. The flow voltage change curves for flow following under the ambient temperature of 30 °C and 50 °C are given respectively, as shown in Figs. 6 and 7.

It can be seen from Figs. 6 and 7 that under different ambient temperatures, the closed-loop control can make the flow of the micro flow controller achieve dynamic stability at different target flow points, indicating that the closed-loop control method has a good tracking effect on the changing flow, and can effectively eliminate the influence of creep and hysteresis on the change of piezoelectric displacement, making the flow

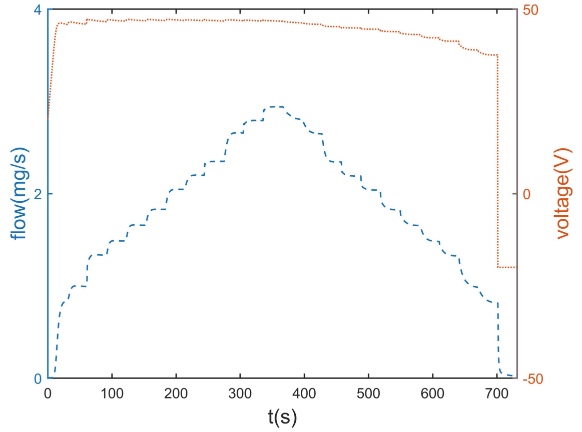

Fig. 6. The flow-voltage curve of flow following on the ambient temperature 30 °C.

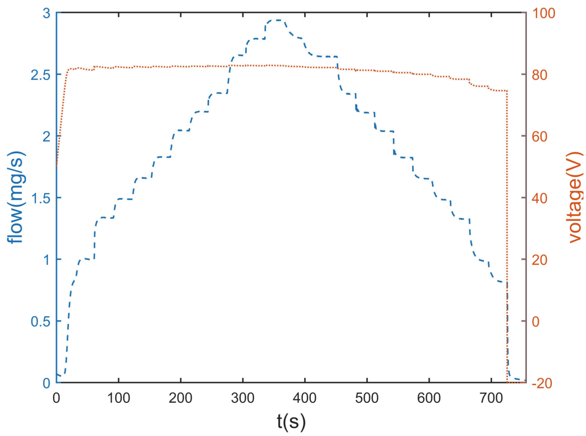

Fig. 7. The flow-voltage curve of flow following on the ambient temperature 50 °C.

control can meet the requirements of high precision. In addition, the piezoelectric ceramic also has the temperature characteristic, that is, the increase of temperature will affect the displacement of the piezoelectric ceramic, and the effect mainly depends on the difference of Curie temperature. In Figs. 6 and 7, when the flow rises from 0 mg/s, the opening voltage of the flow controller varies greatly. At 30 °C, the opening voltage of the piezoelectric drive assembly is about 45 V, while the opening voltage of the piezoelectric drive assembly is about 81 V at 50 °C, indicating that the piezoelectric effect will be significantly reduced at high temperature, that a higher driving voltage is required to make the valve opening reach the same position to meet the requirements of stabilizing to the target flow.

3.2 Power Spectrum Density for Flow

Since the complex fluid movement and friction, flow inlet pressure and ambient temperature change, control algorithm and other factors will make the flow have noise fluctuations. The flow noise will affect the accuracy of scientific detection in the corresponding frequency band, such as the detection of space gravitational wave [16, 17]. This paper will use power spectral density (PSD) to analyse the flow noise under closed-loop control. The equation of power spectral density is given by

$$S_x(\omega) = \lim_{T\to\infty} \frac{1}{2T} |F_x(\omega, T)|^2 \tag{8}$$

$$\begin{aligned} F_x(\omega, T) &= \int_{-\infty}^{\infty} x_T(t)\, e^{-i\omega t} dt \\ &= \int_{-T}^{T} x(t)\, e^{-i\omega t} dt \end{aligned} \tag{9}$$

where, Eq. (8) is the PSD for signal $x(t)$ at frequency ω, T is the sampling period. For the PSD of, there are $x(t) = m(t)$, Eq. (9) the Fourier transform for signal $x(t)$. $x_T(t)$ is the truncated function for $x(t)$, the relation is

$$x_T(t) = \begin{cases} x(t), & |t| \le T \\ 0, & |t| > T \end{cases} \tag{10}$$

With Eqs. (8) to (10), the PSD of flow for the real micro flow control system as shown in Fig. 3 can be calculated when the flow reaches the steady-state under the closed-loop control. Set the sampling number of flow to 1024, the sampling frequency to 5 Hz and 10 Hz respectively, and the ambient temperature to 10 °C and 40 °C and respectively, the PSD of flow for different target flows under closed-loop control for the piezoelectric micro flow controller is shown in Figs. 8, 9, 10, 11, 12 and 13.

As can be seen from Figs. 8, 9, 10, 11, 12 and 13, the PSD of flow for the flow controller under closed-loop control tends to decrease with the increase of frequency, but the performance is also different due to the difference of flow sampling frequency, closed-loop target flow and ambient temperature. In Figs. 7 and 8, under the same ambient temperature and the same target flow, the sampling frequency is smaller, the PSD of flow is greater, especially in the low temperature environment, the difference is more obvious. When the frequency is less than 0.5 Hz, the smaller the sampling frequency, the greater the change of the PSD of flow and the decline slope. When the frequency is greater than 1 Hz, the change of PSD of flow tends to be stable. Therefore, for the micro flow controller with closed-loop control, in order to reduce the effect of flow noise, the sampling frequency of flow should be increased.

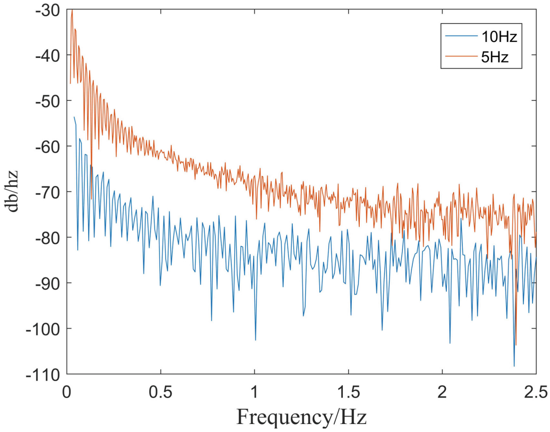

Fig. 8. The PSD of flow at 10 °C with the target flow 0.1 mg/s.

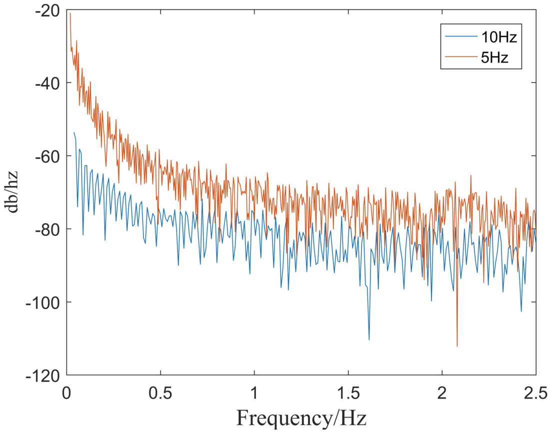

Fig. 9. The PSD of flow at 40 °C with the target flow 0.1 mg/s.

From Fig. 10, at the low temperature of 10 °C, when the frequency is less than 1.5 Hz, the smaller the closed-loop target flow, the greater the PSD of flow. When the frequency is greater than 1.5 Hz, the PSD of flow with different target flows gradually reconstitutes and stabilizes. Form Fig. 11, at the high temperature of 40 °C, when the frequency is less than 1 Hz, the smaller the closed-loop target flow, the greater the PSD of flow. When the frequency is greater than 1 Hz, the PSD of flow with different target flows gradually reconstitutes and stabilizes. It shows that for the closed-loop control of the micro flow controller, the flow noise is significant at the low-frequency band, that the effect of the low-frequency flow noise should be paid attention to meet the needs of different target flows.

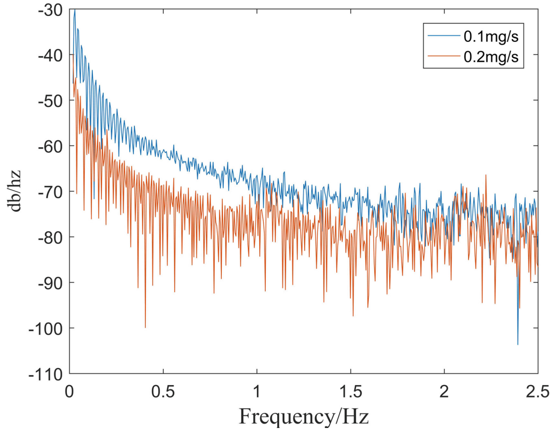

Fig. 10. The PSD of flow at 10 °C with the sampling frequency 5 Hz.

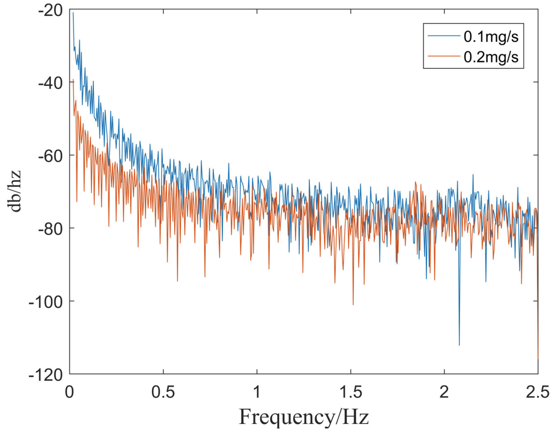

Fig. 11. The PSD of flow at 40 °C with the sampling frequency 5 Hz.

In Fig. 12, when the sampling frequency is 10 Hz and the target flow is 0.1 mg/s, the PSD of flow decreases rapidly when the frequency is less than 0.5 Hz, and there is a sudden change occurs near 2 Hz, then it tends to be stable. In Fig. 13, when the sampling frequency is 5 Hz and the target flow is 0.1 mg/s, the PSD of flow decreases rapidly when it is less than 1 Hz, and then it tends to be stable. Under the two different working conditions, the ambient temperature is different, but the PSD of flow keeps the same changing trend, indicating that the change of the ambient temperature has little effect on the change of flow noise in the closed-loop control of the micro flow controller.

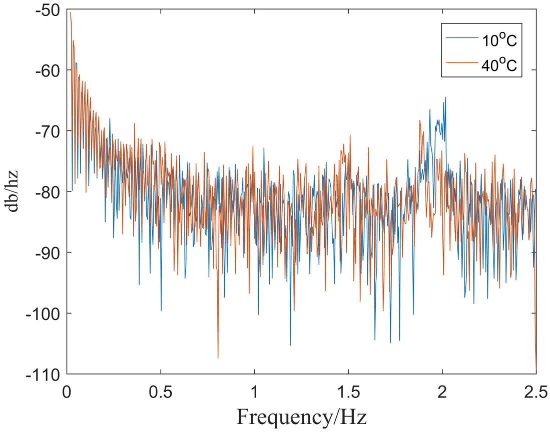

Fig. 12. The PSD of flow with the sampling frequency 10 Hz and target flow 0.1 mg/s.

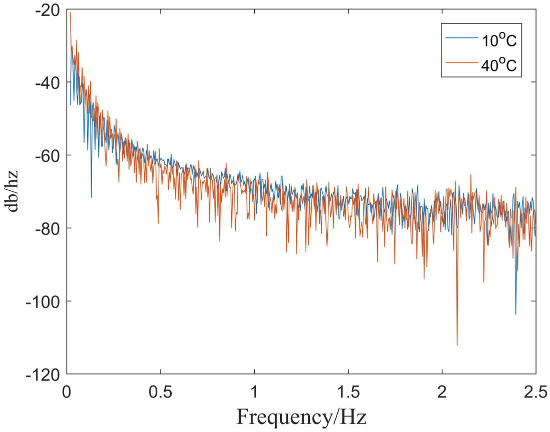

Fig. 13. The PSD of flow with the sampling frequency 5 Hz and target flow 0.1 mg/s.

4 Conclusion

This paper presents a closed-loop control method for the micro flow controller using piezoelectric ceramics as the driving mechanism, and verifies the effectiveness of the closed-loop control on the flow stability and flow following through experiments. It shows that the closed-loop control can effectively eliminate the influence of the creep and hysteresis of the piezoelectric ceramic, so that it can meet the needs of high-precision flow control. In addition, the influence of the flow noise of the micro flow controller with the closed-loop control is analysed, and the PSD of flow under different ambient temperature, flow sampling frequency and closed-loop target flow are given respectively. Through the analysis of the PSD of flow varying with the frequency, it can be seen that the change of the ambient temperature has little effect on the change of the PSD, while for different closed-loop target flows, the flow noise in the low-frequency band changes sharply, so that the sampling frequency should be increased to reduce the effect of the flow noise.

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