Research of control method for pneumatic control of pneumatic microchips

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A B S T R A C T

A novel composite control method for actuated chamber air pressure of pneumatic microfluidic chip via a three-way electromagnetic microvalve is presented in this paper. The purpose of the control methods is to improve air pressure controlling precision for pneumatic control. By using the Bang-Bang (on-off) controller for pneumatic control, the step-response time, air pressure steady-state accuracy, and air pressure fluctuations are performed with different maximum thresholds and minimum thresholds. Moreover, by using the k (proportional) plus PWM (Pulse-Width Modulation) control method for pneumatic control, the step-response time, air pressure steady-state accuracy, and air pressure fluctuations are performed with different carrier frequencies and carrier amplitudes. Both advantages and disadvantages of the two control methods are compared and analyzed based on the experimental data. According to the variable volume of the actuated chamber and the response characteristics of the three-way electromagnetic microvalve, the composite control method of the Bang-Bang plus k plus PWM is developed to control the actuated chamber air pressure. The experimental results show that when the absolute air pressure of the actuated chamber is set to 150kPa, the rising time is 69.3ms, which is about 8.0ms shorter than that of the k+PWM control method alone. The steady-state error is reduced from 0.90kPa to 0.65kPa, and the air pressure steady-state fluctuation is reduced from 1.60kPa to 0.90kPa, compared with the Bang-Bang control method alone.

1. Introduction

In recent operational years, pneumatic microfluidic chips have developed from simple operational units to microfluidic Large Scale Integration (mLSI), which are more and more successfully used in the molecular biological, chemical analysis, environmental monitoring, and biomedical systems with the advantages of reduced sample consumption, faster analysis and response time, as well as increased automation and system functional integration [1,2]. The polydimethylsiloxane (PDMS) basic components on the pneumatic microfluidic chip, such as peristaltic micro pumps [3,4], pneumatic micro valves [5,6], pneumatic micro mixers [7,8], and pneumatic digital logic circuits [9,10], have become the most widely-used because its control system and air pressure generation are usually off chip. The pneumatic micro actuator is the core part of a pneumatic microfluidic chip [11,12]. Therefore, the real-time, accurate, and fast control of the air pressure in the actuated chamber is the key to realize the accurate control of the liquid flow in the microchannel. In recent years, focusing on the actuated performance underifferent air pressures, some researchers have paid attention to modified geometries of the pneumatic micro actuator. Lee and coworkers designed and investigated a finite element model of the pneumatic micro actuator components to calculate the displacement distribution of membrane deflection under pressures [13]. The authors of [14] had analyzed and understood different factors influencing the performance of the pneumatic micro actuator according to the theory of membrane distortion and gave the computational model about sealing surface area versus membrane deflection. Lau et al. investigated that the dynamics of the pneumatic micro actuators (microvalves) on-chip was indeed influenced by not only the configurations, such as membrane thickness, actuated air pressure but also the levels of design complexity and positions in the devices [15]. The control performance, however, such as response time, air pressure fluctuation, and steady-state error, has not yet been systematically studied.

Additionally, there is still much work to be done on the actuated chamber air pressure precise control method. Li’s research group reported that a proportional–integral controller was integrated with the

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Nomenclature

e(t) difference between set air pressure and the real air pressure (kPa)

r(t) set air pressure of the actuated chamber (kPa)
p(t) real air pressure of the actuated chamber (kPa)
u(t) controller output (kPa)

E_{max} upper limit value of Bang-Bang controller (kPa)

E_{min} lower limit value of Bang-Bang controller (kPa)
k proportional controller

PWM Pulse-Width Modulation controller

P_{ac} absolute air pressure of the actuated chamber (kPa)

k_{p} proportional coefficient of k controller

r_{c} set absolute air pressure value of the actuated chamber (kPa)

\Delta P_{\text{fluc}} air pressure fluctuation (kPa)

\varepsilon_{ed} steady-state error (kPa)

t response time (s)

f_{c} carrier frequency of PWM controller (Hz)

e_{c} carrier amplitude of PWM controller (kPa)

\Delta P_{\text{upper}} upper limit of air pressure fluctuation (kPa)

\Delta P_{\text{lower}} lower limit of air pressure fluctuation (kPa)

P_{tr} tracking error (kPa)

Bang-Bang controller, carrier frequencies, and carrier amplitudes of the k plus PWM controller. Both advantages and disadvantages of the two control methods are compared and analyzed using respective experimental data. According to the variable volume of the actuated chamber and the response characteristics of the three-way electromagnetic microvalve, the composite control method of the Bang-Bang plus k plus PWM is developed to control the actuated chamber air pressure. The effectiveness of the composite control method is validated by the response time, air pressure tracking effect, and steady-state precision of experimental results.

2. Main performance of control system

The fluid driving setup for the three-layer PDMS microfluidic chip includes a supply source of compressed air with two suits of pressure regulator and a scrubbing bottle, as shown in Fig. 1. Several components are needed to supply the compressed air cleanly and safely to the microfluidic systems, such as a compressed air tank or an air compressor, two pressure-reducing valves, and air filters. Here, a compressed-air driven liquid system is used for controlling the accurate differential pressure for the liquid microchannel, which can be used for a variety of microfluidic applications that require a rapid dynamic response and precise control of multiple inlet streams. The three electromagnetic microvalve linked to the air microchannel is used to control the air pressure of the pneumatic microchip.

The designed air pressure control system based on the three-way electromagnetic microvalve should realize the two main functions, air pressure acquisition and appropriate control methods. The air pressure control system needs to collect the air pressure signal in the actuated chamber quickly and in real time. In the control system studied in this paper, the air pressure feedback is used to realize the closed-loop control of the actuated chamber air pressure. The real-time acquisition performance of the air pressure signal largely determines the control accuracy of the actuated chamber. In order to achieve good control accuracy of the air pressure in the actuated chamber, it is necessary to select the pressure sensor with appropriate accuracy and the high-resolution data acquisition card to ensure the control system has good real-time data acquisition performance and acquisition accuracy. Combined with the computer data processing technology, a data acquisition system is constructed to ensure fast real-time data acquisition. The air pressure closed-loop control system needs to adopt appropriate control methods and output accurate pulse control signals. The control method is the core of the control system. According to the characteristics of the actuated chamber of the proposed pneumatic micro actuator, the appropriate control method should be selected to improve the control precision of the actuated chamber air pressure. Step response, air pressure fluctuation, and steady-state error are the main performance indexes of the actuated chamber air pressure closed-loop control system. The test results of different control methods are compared and analyzed, and the optimal control method of the system is proposed.

3. Control method research of the actuated chamber air pressure

3.1. Bang-Bang control method

The control principle of Bang-Bang control is to divide the state space into two regions. One region corresponds to the maximum positive value of the control variable, and the other region corresponds to the maximum negative value of the control variable. The interface between the two regions is called the switching surface, and the output value of the system fluctuates around the switching surface. The key of Bang-Bang control is to select the optimal switching surface according to the characteristics of the controlled system.

In the air pressure control system in this paper, because the three-way electromagnetic microvalve developed only has two working states
of "on" and "off", the air pressure closed-loop control system adopts the typical Bang-Bang digital control method. Set the upper and lower limit values, take the interval of the two limit values as the control area, the controlled quantity – the air pressure of the actuated chamber will switch between the two set thresholds, and the air pressure output value is stable within the set threshold value with a certain control precision.

Using the Bang-Bang control method can avoid frequent opening and closing of the three-way electromagnetic microvalve and extend its service life. The block diagram of Bang-Bang control system for actuated chamber air pressure is shown in Fig. 2. When \( e(t) \) of the difference between the set air pressure \( r(t) \) and the real air pressure \( p(t) \) in the actuated chamber is greater than the upper limit value \( E_{\text{max}} \), the Bang-Bang controller outputs \( u(t)=1 \), indicating the "on" state, that is, the inlet of the three-way electromagnetic microvalve opens and the outlet of the three-way electromagnetic microvalve closes, and the air pressure in the actuated chamber increases to the set threshold range. When the deviation \( e(t) \) is less than the set lower limit value \( E_{\text{min}} \), the Bang-Bang controller outputs \( u(t)=0 \), indicating the "off" state, that is, the inlet of the three-way electromagnetic microvalve is closed, the outlet of the three-way electromagnetic microvalve is opened, and the air pressure in the actuated chamber drops to the set threshold range.

The Bang-Bang control method is used to make the air pressure output of the actuated chamber fluctuate up and down within the threshold value. The key of the control method is to choose the appropriate upper and lower control threshold value. The selection of the control threshold should take into account the dynamic response speed of the three-way electromagnetic microvalve and the control accuracy of the air pressure in the actuated chamber. On the contrary, if the threshold is too small, the three-way electromagnetic microvalve will be opened and closed frequently. The advantages of the Bang-Bang control method cannot be reflected.

3.2. PWM control method

When the air pressure control system works, the controller compares and calculates the air pressure signal fed back by the miniaturized pressure sensor with the set-value, outputs the PWM pulse width signal to control the opening and closing of the inlet and outlet of the three-way electromagnetic microvalve, and then controls the change of the air pressure in the actuated chamber.

Proportional control \( k \), as the most classical control method, has good robustness, easy to implement, and other characteristics. Therefore, the \( k \)-PWM control method is used in this paper, the output signal of the \( k \) controller is the input signal of the PWM controller, and control the opened or closed average time valve of the three-way electromagnetic microvalve, the final control the inlet/outlet air flow by the three-way electromagnetic microvalve, to control the actuated chamber air pressure. It is noted that, in theory, it is difficult to shorten the pressure response time of the actuated chamber by adding the \( k \) controller in front of the PWM controller. Because when the PWM signal is used alone, the "on" signal is sent to the three-way electromagnetic microvalve, and the inlet of the three-way electromagnetic microvalve opens, the response time is the shortest when the pressure in the actuated chamber changes from atmospheric pressure for the first time to the set-value. Proportional control \( k \) is added in this paper to improve the control accuracy of the air pressure in the actuated chamber and reduce the air pressure fluctuation in the steady-state process, which requires the control method to be simple, flexible, and fast.

The \( k \)-PWM control method is used to control the air pressure of the actuated chamber, and its control block diagram is shown in Fig. 3. The measured value \( p(t) \) of the miniaturized pressure sensor is compared with the air pressure set-value \( r(t) \), and the difference value \( e(t) \) is obtained. After being adjusted by the \( k \) controller, the pulse modulation is controlled by PWM and converted into the high and low levels of the
pulse signal. If the output is high level, that is, \( u(t) = 1 \), the inlet of the three-way electromagnetic microvalve is opened, and the outlet of the three-way electromagnetic microvalve is closed. The actuated chamber is inflated, and the air pressure rises. If the output is low, that is, \( u(t) = 0 \), the inlet of the three-way electromagnetic microvalve is closed, the inlet of the three-way electromagnetic microvalve is opened, the actuated chamber exhaust, the air pressure falls back to the set-value, to achieve the stability of the air pressure in the actuated chamber.

The key to PWM control of the air pressure in the actuated chamber is to select the appropriate PWM modulation frequency and amplitude. For the PWM control method, the higher the modulation frequency, the higher the modulation accuracy. The selection of modulation frequency should take into account the dynamic response speed and control precision of the three-way electromagnetic microvalve. The k+PWM control method is adopted in this paper. The k control is taken as the pre-control of PWM, and \( k_p \) is the proportional coefficient of the k controller.

3.3. Composite control method

According to the characteristics of the Bang-Bang control method and the k+PWM control method, and based on the effect of each control strategy on the air pressure control of the actuated chamber, the composite control method of Bang-Bang+k+PWM is proposed to control the air pressure of the actuated chamber, the Bang-Bang control method is used in the response process of the actuated chamber, which made it reach the steady-state region quickly. After entering the steady-state process, the k+PWM control method is adopted to improve the steady-state accuracy and reduce the air pressure fluctuation. The composite control block diagram of actuated chamber air pressure is shown in Fig. 4.

The error value is used to judge the control system is in a response process or a steady-state process. When the absolute value of the error value is greater than 5% of the set-value, the control system is considered to be in the response process, and the system adopts the Bang-Bang control method. When the absolute value of the error value is less than or equal to 5%, the control system is considered to be in the steady process, and the system automatically switches to the k+PWM control method to control the actuated chamber air pressure in the steady-state process.

4. Experimental setup of control system

A single electromagnetic microvalve with a high-speed electromagnetic actuator and a PDMS electromagnetic microchannel. Two electromagnetic microvalves constitute a PDMS three-way electromagnetic microvalve. Detailed information about the specific structure and working principle of the three-way electromagnetic microvalve can be found in our previous study [23]. The three-way electromagnetic microvalve is integrated with the pneumatic micro actuator to form a control system, as shown in Fig. 5(a). The volume of the actuated chamber is 3x3x1mm, which is equivalent to the volume of a microchannel with a length of 180mm, a width of 500μm, and a depth of 100μm. This length is in line with the conventional design size of a pneumatic microfluidic chip. The miniature pressure sensor XCQ-062-30A produced by Kulite Company in the United States is adopted as the measuring module, with a weight of 0.17g, as shown in Fig. 5(c). The miniaturized pressure sensor works in the absolute air pressure mode, the natural frequency is 300kHz, the output voltage signal is 0–100mV, and the corresponding sensor range is 0–3.0x10⁵Pa. Moreover, the miniaturized pressure sensor can work in the sinusoidal wave environment where the steady-state acceleration and linear vibration are less than 1000g, so the disturbance of the mechanical vibration of the system itself to the air pressure test results can be ignored. Because the sensor can only test non-conductive and non-corrosive liquid or air, the high purity nitrogen is used as the working medium of the air pressure control system in this test.

The steel pipe head of the self-made perforator shall be finely and uniformly polished into uniform convex cones. Otherwise, when drilling on the PDMS material, the wall surface drilled will not be vertical, and severe cracking or even air leakage will be caused to the PDMS substrate. The head size is φ0.45mm×0.60mm stainless steel perforator, which is used to make the connection hole between the pneumatic actuator and the three-way electromagnetic microvalve. A stainless steel perforator with head size φ1.7mm×2.0mm is used to drill PDMS substrates for mounting miniature pressure sensors. A micrograph of the miniaturized pressure sensor mounted in the actuated chamber is shown in Fig. 5(b).

The test bench of the air pressure control system is shown in Fig. 6, which mainly consists of the controlled object—the micro actuator with the integrated three-way electromagnetic microvalve, power module,
data acquisition module—the miniature pressure sensor, signal amplification module, data processing module—the computer and air source—the air supply with the precision pressure reducing valve, etc.

The power module includes two parts, which supply power to the three-way electromagnetic microvalve and the miniaturized pressure sensor. The miniaturized pressure sensor is powered by a 10V DC power supply, which is supplied by the voltage signal on the signal amplifier module. The three-way electromagnetic microvalve is powered by the digital output of the industrial computer after power amplification.

Because this control system needs to acquire the air pressure of 10~100kPa magnitude, the sensor signal is 10mV magnitude. Both are very close to the external interference signal, which can easily cause the inaccuracy of measurement and control. Therefore, the self-made signal amplification module is used to amplify the air pressure signal. The amplifier module is mainly composed of high precision four-channel operational amplifier OP497 and high precision AD620. The OP497 has very low offset voltage (less than 50μV) and low drift (less than 0.5μV/°C) characteristics, and the open-loop gain is more than 2000V/mV, which can ensure the application to achieve high linearity. The AD620 is a low-cost and high-precision instrument amplifier. Its gain can be set using only one external resistor. The amplification factor of the signal amplification module is designed to be 100 times, and the output signal of the miniaturized pressure sensor is amplified from 0-100mV to 0-10V.

PCI-1710-CE acquisition card of Advantech Co., Ltd of China is adopted as the data acquisition module, which has 16 analog input ports and 2 analog output ports, can meet the requirements of the control system. The differential connection method is used to collect the output signal of the miniaturized pressure sensor, which can effectively suppress the external interference. The signal acquisition range of the analog input port is 0-10V. Two analog outputs are connected to two inputs of the power amplifier to drive and control the opening and closing of the three-way electromagnetic microvalve. A linear power supply is used to supply power to the signal amplifying circuit to reduce the ripple coefficient.
5. Experimental results analysis

In this experimental research, the step-response time, steady-state air fluctuation and steady-state error of the actuated chamber air pressure are the main performance index of the pneumatic control system. The experiment is conducted for each control strategy in different situations using step input signal. The results show the reliability and effectiveness of the proposed composite control strategy.

5.1. Bang-Bang

The upper threshold of the Bang-Bang controller is set to 1kPa, the lower threshold is set to 0kPa, the absolute air pressure of the air source is 220kPa, the absolute air pressure set-value of the actuated chamber $r_c$ is set to 130kPa, 150kPa, and 200kPa, respectively. The equivalent volume of the actuated chamber is 9μL, and there is no outlet flow. The step-response curve of actuated chamber absolute air pressure $P_a$ is shown in Fig. 7.

As shown from Fig. 7(a), the rising time is about 44.3ms when the absolute pressure set-value $r_c$ is 130kPa, the rising time is 61.2ms when $r_c$ is 150kPa, the rising time is 80.0ms when $r_c$ is 180kPa, and the rising time is 92.4ms when $r_c$ is 200kPa. There is no obvious overshoot during the rising process, the pressure rising time in the actuated chamber increases with the increase of the air pressure set-value $r_c$ of the actuated chamber, and the air pressure rising curves do not coincide. According to the characteristics of Bang-Bang control method, steady-state pressure fluctuation and steady-state error are inevitable in steady-state. As shown from Fig. 7(b) and Fig. 7(c), the steady-state pressure fluctuation $\Delta P_{\text{fluc}}$ and steady-state error $e_a$ both increase with the increase of the air pressure set-value $r_c$. The frequency of pressure fluctuation $\Delta P_{\text{fluc}}$ in the steady-state phase decreases with the increase of the air pressure set-value $r_c$. The reason is that the higher the air pressure in the actuator chamber, the lower the switching frequency regulated by the three-way electromagnetic microvalve.

Under the above test conditions, $r_c$ is set to 150kPa, the upper threshold $E_{\text{max}}$ of Bang-Bang controller is set to 1kPa, and the lower threshold $E_{\text{min}}$ is set to -2kPa, -1kPa, -0.5kPa, and 0kPa, respectively. Under different lower threshold set-values of the Bang-Bang controller, the step-response characteristics of air pressure in the actuated chamber are studied. The test results are shown in Fig. 8.

When the lower threshold is set to different values, the step-response time of the air pressure in the actuated chamber is basically unchanged. In the steady-state process, the air pressure fluctuation $\Delta P_{\text{fluc}}$ decreases with the decrease of the absolute value of the lower threshold, but the air pressure fluctuation $\Delta P_{\text{fluc}}$ all exceeds the region of the upper and lower threshold controlled by the Bang-Bang controller, because the active response of the three-way electromagnetic microvalve lags behind the air pressure change in the actuated chamber. The pressure upper value $\Delta P_{\text{upper}}$ decreases with the decrease of the absolute value of the control threshold. In contrast, the lower value of $\Delta P_{\text{fluc}}$ air pressure fluctuation is 1.60kPa and does not change with the decrease of the absolute value of the lower threshold. The minimum value of $\Delta P_{\text{upper}}$, the upper limit of air pressure fluctuation, is about 0.65kPa, which exceeds the air pressure set-value and does not change with the decrease of the absolute value of the lower threshold.

Under the above test conditions, $r_c$ is set to 150kPa, the lower threshold $E_{\text{min}}$ of the Bang-Bang controller is set to -1kPa, and the upper threshold $E_{\text{max}}$ is set to 2kPa, 1kPa, 0.5kPa, and 0kPa, respectively. Under the different upper threshold $E_{\text{max}}$ the step-response characteristics of the air pressure in the actuated chamber are studied. The test results are shown in Fig. 9.

When the upper threshold is set to different values, the step-response time of the air pressure in the actuated chamber is basically unchanged. After entering the steady-state process, the air pressure fluctuation value
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Fig. 8. Experimental results of $P_n$ with different $E_{\text{min}}$ using Bang-Bang ($E_{\text{max}}$ is 1kPa). (a) Step-response curves of $P_n$ with different $E_{\text{min}}$; (b) $\Delta P_{\text{fluc}}$ with different $E_{\text{min}}$; (c) $\Delta P_{\text{upper}}$ with different $E_{\text{min}}$.

Fig. 9. Experimental results of $P_n$ with different $E_{\text{max}}$ using Bang-Bang ($E_{\text{min}}$ is -1kPa). (a) Step-response curves of $P_n$ with different $E_{\text{max}}$ using Bang-Bang; (b) $\Delta P_{\text{fluc}}$ with different $E_{\text{max}}$; (c) $\Delta P_{\text{lower}}$ with different $E_{\text{max}}$. 
Δp_{\text{fluc}} decreases as the absolute value of the upper threshold of the set Bang-Bang controller decreases. However, the lowest value of Δp_{\text{fluc}} air pressure fluctuation is 1.60kPa and does not change because of the absolute value of the set upper threshold of the Bang-Bang controller decreases. Moreover, the lower limit Δp_{\text{lower}} of air pressure fluctuation decreases with the decrease of the absolute value of the threshold value of the Bang-Bang controller, which is closer to the set-value. However, the lower limit Δp_{\text{lower}} of the steady-state air pressure fluctuation is about 0.90kPa, which exceeds the set-value of the absolute value of the upper threshold of the Bang-Bang controller. Moreover, it does not change with the reduction of the absolute value of threshold on the Bang-Bang controller.

The experimental results show that the air pressure in the actuated chamber can be controlled basically by the Bang-Bang controller, and the air pressure response speed is fast. However, there are certain steady-state errors and air pressure fluctuation. When the absolute air pressure of the actuated chamber is set to 150kPa, the steady-state error is about 0.90kPa, and the air pressure fluctuation is about 1.60kPa. Therefore, in order to further reduce the steady-state error and air pressure fluctuation in the steady-state process of the actuated chamber air pressure and improve the control effect, it is necessary to continue to optimize the control strategy of the control system.

5.2. k+pWM

The absolute air pressure of the air source of the actuated chamber is 220kPa, the PWM carrier frequency f_c is set to 50Hz, the absolute air pressure of the actuated chamber is r_c is set to 150kPa, the error is e_c is set to 1kPa, the equivalent volume of the actuated chamber connected at the outlet is 9μL, and there is no outlet flow. When there is a proportional controller in front of the PWM controller, the air pressure response characteristic curve of the actuated chamber is shown in Fig. 10.

As shown from Fig. 10(a), the air pressure rising time of the actuated chamber is about 75.0ms, and different k_p set-values of the proportional controller have almost no influence on the air pressure rising time, and there is no overshoot phenomenon and obvious transition process. When k_p is set to 1, the steady-state error is about 1.0kPa, and the air pressure fluctuation is about 1.3kPa. When k_p is set to 3, the steady-state error is about 0.65kPa, and the air pressure fluctuation is about 1.0kPa. The steady-state accuracy is improved to a certain extent, and the air pressure fluctuation is reduced to a certain extent. It should be noted that it has little influence on the step-response curve of the air pressure when k_p is set to [2, 5, 4]. Therefore, the test curves are compared in this paper when k_p is set to 3 and k_p is set to 1, respectively. Moreover, noticed that k_p is set to 1, which means that there is no proportional controller. As shown in Fig. 10(c), compared with the results of the Bang-Bang control method (Figs. 7-9), the rising time is extended by about 14.0ms, but the steady-state error is reduced by about 0.25kPa, and the air pressure fluctuation is reduced by about 0.70kPa.

Under the above test conditions, the carrier amplitude e_c is set to 1kPa, and the carrier frequency f_c is set to 10Hz, 20Hz, 50Hz, and 100Hz, respectively. The step-response curves of the air pressure in the actuated chamber with different carrier frequencies are shown in Fig. 11.

As shown from Fig. 11(a), the absolute air pressure set-value of the actuated chamber is 150kPa, and the constant rising time of different carrier frequencies is about 75.0ms. The step-response time of the air pressure in the actuated chamber is almost unchanged, and there is no obvious overshoot phenomenon, indicating that the carrier frequency has little influence on the step-response time of the air pressure in the actuated chamber. As shown from Fig. 11(b) and (c), when the carrier amplitude e_c is 1kPa, the air pressure fluctuation decreases with the increase of carrier frequency, and Δp_{\text{fluc}} is greater than or equal to e_c, because the higher the PWM carrier frequency is, the finer the air pressure modulation result. The steady-state error value is almost equal to the carrier amplitude set-value (1kPa) and slightly greater than 1kPa at low carrier frequencies (f_c is set to 10Hz or f_c is set to 20Hz). The experimental data show that increasing the PWM carrier frequency can effectively improve the steady-state accuracy of the system air pressure and reduce the air pressure fluctuation.

Under the same test conditions, when the air pressure of the actuated chamber is set to 150kPa, the carrier frequency f_c is set to 50Hz, and the carrier amplitude e_c is set to 0.1kPa, 0.5kPa, 1kPa, and 2kPa, respectively. The step-response curve of the air pressure in the actuated chamber is shown in Fig. 12(a). As shown from Fig. 12(b) and Fig. 12(c),
Fig. 11. Experimental results of $P_n$ with different $f_c$ ($e_c$ is 1kPa). (a) Step-response curves of $P_n$ with different $f_c$; (b) $\Delta p_{\text{fluc}}$ with different $f_c$; (c) $e_n$ with different $f_c$.

Fig. 12. Experimental results of $P_n$ with different $e_c$ ($f_c$ is 50Hz). (a) Step-response curves of $P_n$ with different $e_c$; (b) $\Delta p_{\text{fluc}}$ with different $e_c$; (c) $e_n$ with different $e_c$. 
when the set-value of carrier amplitude \( e_c \) is set to greater or equal to 1kPa, the air pressure fluctuation and steady-state error in the actuated chamber are basically within the set range. When the carrier amplitude set-value \( e_c \) is less than or equal to 0.5kPa, the air pressure fluctuation is about 0.90kPa, and the steady-state error is about 0.65kPa. This indicates that the system pressure steady-state error limit is about 0.65kPa, and the pressure fluctuation limit is about 0.90kPa.

According to the characteristics of PWM and proportional control strategies, the k+PWM control method for the actuated chamber air pressure of the developed pneumatic micro actuator is experimented and studied. The experimental results show that the k+PWM control method has no obvious air pressure overshoot in the actuated chamber, and the step-response time is longer than that of the Bang-Bang control method. The reason is that the carrier amplitude of the PWM is not set properly in the rising stage, which will affect the rising time. The PWM control method can effectively reduce the steady-state air pressure fluctuation, but there is a certain steady-state error. The k+PWM control method has little effect on the response time of the system but can effectively improve the steady-state accuracy.

### 5.3. Composite control method

According to the characteristics of the Bang-Bang control and the k+PWM control, and based on the effect of each control strategy on the air pressure control of the actuated chamber, the composite control method of Bang-Bang+k+PWM is proposed to control the air pressure of the actuated chamber, and the response process is Bang-Bang control method, which made it reach the steady-state region quickly. After entering the steady-state process, the k+PWM control method is adopted to improve the steady-state accuracy and reduce the air pressure fluctuation.

The error value is used to judge the response process and steady-state process of the system. When the absolute value of the error value is greater than 5% of the set-value, it is considered the response process, and the system adopts the Bang-Bang control method. When the absolute value of the error value is less than or equal to 5%, it is considered that the system response enters the steady process, and the system automatically switches to the k+PWM control method to control the actuated chamber air pressure in the steady-state process.

Under the same test conditions, the absolute air pressure of the air source is 220kPa, and the absolute air pressure of the actuated chamber is set to 150kPa. When there is no load flow, the step-response process of the air pressure in the actuated chamber is shown in Fig. 13(a). The inflating rising time of the actuated chamber is 69.3ms, which is shorter than that of k+PWM control alone. The steady-state error is 0.65kPa, and the air pressure fluctuation is 0.90kPa, while the air pressure fluctuation and steady-state error are much lower than that when using Bang-Bang control alone. The steady-state effect is the same as k+PWM control, which meets the design requirements of the control system.

Other test conditions remain unchanged, and the air pressure change period is set to 0.25s. When the air pressure set-value of the actuated chamber \( r_c \) changes at 150kPa, 130kPa, 180kPa, and 120kPa, Fig. 13(b) and Fig. 13(c) respectively show the change of the actuated chamber pressure and the change of the tracking error, which reflect the system stability and the system tracking accuracy. As shown from Fig. 13(b), the air pressure tracking process of the actuated chamber is basically stable, with no overshoot and a good tracking effect. At the step change, the steady-state process can be reached quickly, and the steady error is small. The response delay phenomenon of the air pressure is not obvious at the step of tracking a small pressure difference signal (180kPa−120kPa). At the step of tracking a large pressure difference signal (180kPa−120kPa), there is a certain pressure response hysteresis. The hysteresis time is about 18.0ms, as shown in Fig. 13(c). Pressure hysteresis exists in the system, which may be caused by the compressibility of the air and the failure to recover the deformation of the high elastic actuated chamber when the air pressure is reduced dramatically.

### 6. Conclusion and future work

The control effects of the above three control methods are shown in Table 1. These three control methods can realize rapid response and steady control of the air pressure in the actuated chamber. However, under the control of Bang-Bang, the steady-state effect of the actuated chamber air pressure is poor, and the steady-state error and air pressure fluctuation are large. Under the control of k+PWM, the steady-state performance is greatly improved, but the rising time is longer. The Bang-Bang+k+PWM composite control method is adopted, and the advantages of the two control methods are combined to achieve good results in the dynamic response characteristics and steady-state characteristics of the actuated chamber air pressure.

According to the dynamic response characteristics of the three-way electromagnetic microvalve and the variable volume characteristics of the actuated chamber of a pneumatic microfluidic chip, the control method for the air pressure in the actuated chamber is studied to shorten the air pressure rising time of the actuated chamber, improve the steady-state precision, and reduce the air pressure steady-state fluctuation. The experimental study of the actuated chamber air pressure is carried out by using the Bang-Bang control method. The step rising time, steady precision, and air pressure steady-state fluctuation are analyzed under different upper threshold and lower threshold settings. The k+PWM control method is used to control the actuated chamber air pressure. The effects of the PWM carrier frequency and carrier amplitude on step rising time, steady-state accuracy, and air pressure steady-state fluctuation are analyzed. By comparing the experimental results, the Bang-Bang+k+PWM composite control method is proposed, and the experimental results are analyzed. When the absolute air pressure of the actuated chamber is set to 150kPa, the rising time is 69.3ms, which is about 8.0ms shorter than that of the k+PWM control method alone. The steady-state error is reduced from 0.90kPa to 0.65kPa, and the air pressure steady-state fluctuation is reduced from 1.60kPa to 0.90kPa, compared with the Bang-Bang control method alone.

There is little change of the rise time of the three control methods from the test results, and the rise time of the composite control method is slightly longer than that of the Bang-Bang control method. However, the response time of the composite control method can meet most application requirements of pneumatic microfluidic chips. Droplet separation chip based on the particle number, for example, to generate every two contains the same number of particles of liquid droplets should be less than the time interval between the droplets by detecting area of time - 100 ms, which requires the control time should be less than 100 ms, if the response time is greater than the time interval, the sorting error rate will increase rapidly [24,25]. Moreover, the steady-state accuracy of the composite control method is the best of the three control methods.

Technologically, there are many applications of microfluidic pneumatic on-chip PDMS valves, micropumps, and mixers have been published in various academic journals [26–28]. The pneumatic components are inflated or deflated by opening or closing the external air source. The disadvantages of on-off control are usually low accuracy and no automatic correction ability. The composite control method proposed in this paper can effectively improve the steady-state accuracy and greatly reduce the air pressure steady-state fluctuation while considering the air pressure rising time of the actuated chamber, which provides

| Table 1 Control effect comparison (\( r_c \) is 150kPa) |
|-----------------|-----------------|-----------------|-----------------|
| Number | Properties | Bang-Bang | k+PWM | composite control |
| 1 | rising time/ \( t \) (s) (10%−90% of the steady-state value) (ms) | 61.2 | 75.0 | 69.3 |
| 2 | Steady-state error/ \( e_c \) (kPa) | 0.90 | 0.65 | 0.65 |
| 3 | Pressure fluctuation/ \( 5P_{fluc} \) (kPa) | 1.60 | 0.90 | 0.90 |
an effective control method for the subsequent experimental research of the pneumatic microfluidic chip system. The microfluidic devices use pneumatic internal valves that are controlled by external solenoid valves to realize the pneumatic actuation for multilayer microfluidics. External solenoid valves and a control system are needed for pneumatic microchips. The structure and operating mode of the proposed three-way electromagnetic is similar to the external solenoid valves, such as SMC and FESTO valve array for off-board pneumatic control of multilayer microchips. Therefore, the proposed composite control method can be expand to other pneumatic microfluidic chip system, if the chip is made of elastic material.

The purpose of the composite control method in this paper is to improve air pressure controlling precision for microfluidic pneumatic control. The novel pneumatic control method provides higher precision automatic control technology for microfluidic chips with high integration and complex reaction functions. Therefore, future work for this research is applied the control method to various pneumatic microfluidic chips for life sciences, physical chemistry, food safety, drug development, disease diagnosis and environmental testing, etc.

**Declaration of competing interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

![Figure 13](image_url) - Experimental results of $P_n$ using the composite control method. (a) Step-response curve of $P_n$ using the composite control method; (b) $P_n$ change process of the actuated chamber tracking step signal; (c) $P_n$ change process.

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**References**


