Shi et al.
Chinese Journal of Mechanical Engineering (2022) 35:44
https://doi.org/10.1186/s10033-022-00697-1

Chinese Journal of Mechanical Engineering

ORIGINAL ARTICLE Open Access

Gas Leakage Detection and Pressure Difference Identification by Asymmetric Differential Pressure Method

Yan Shi[1], Jiaqi Chang[1], Yixuan Wang[1*], Xuelin Zhao[2,3], Qingzhen Zhang[1*] and Liman Yang[1]

Abstract

Currently, the measurement methods for pneumatic system leakage include bubbling, ultrasonic, and pressure detection methods. These methods are sensitive to high-precision sensors, long detection times, and stable external environments. The traditional differential pressure method involves severe differential pressure fluctuations caused by environmental pressure fluctuations or electromagnetic noise interference of sensors, leading to inaccurate detection. In this paper, a differential pressure fitting method for an asymmetric differential pressure cylinder is proposed. It overcomes the limitation of the detection efficiency caused by the asynchronous temperature recovery of the two chambers in the asymmetric differential pressure method and uses the differential pressure substitution equation to replace the differential calculation of the differential pressure. The improved differential pressure method proposes an innovation based on the detection principle and calculation method. Additionally, the influence of the parameters in the differential pressure substitution equation on the leakage calculation results was simulated, and the specific physical significance of the parameters of the differential pressure substitution equation was explained. The experiments verified the fitting effect and proved the accuracy of this method. Compared with the traditional differential pressure method, the maximum leakage deviation of inhibition was 0.5 L/min. Therefore, this method can be used to detect leaks in air tanks.

Keywords: Leakage detection, System identification, Asymmetric tank, Pneumatics, Measurement, Flow characteristics

1 Introduction

Research on airtightness is of great significance for servo control [1], pneumatic springs [2], surgical equipment [3], and semiconductor manufacturing [4]. Pneumatic servo control collects the flow information of some positions in the pneumatic mechanical coupling system to accurately control changes, such as the position, speed, and acceleration of the controlled body. The pneumatic spring was filled with compressed air in a sealed container, and its elastic effect was realized using the compressibility of the gas. However, these systems require different degrees of sealing. When leakage occurs, the output force or output displacement of the pneumatic servo control changes significantly, the pneumatic spring cannot meet the elastic requirements, and the surgical equipment cannot reach the appropriate position of the patients, which has a significant impact on production and life. Therefore, research on airtightness is a key research topic in the field of pneumatic power.

Existing airtightness research includes the bubbling method, acoustic emission detection method, and pressure detection method. The ultrasonic method is a type of acoustic emission detection method that has been extensively researched and improved [5–7]. However, the measurement of the ultrasonic method is

*Correspondence: magic_wyx@163.com; zhangqz@buaa.edu.cn
[1] School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China
Full list of author information is available at the end of the article

significantly affected by the environment, and the external air flow disturbance easily interferes with ultrasonic detection. When the measured part is placed in a harsh environment, it is difficult to accurately determine the occurrence and degree of leakage using this method. At the same time, different measuring people, different measuring machines, and different measuring positions or angles might also yield different measurement results. Additionally, some scholars have studied pipeline leakage detection [14, 15]; however, their detection methods rely heavily on the logical relationship between pipelines, which cannot be applied to a pneumatic system with a complex structure.

The differential pressure and direct pressure methods belong to the pressure detection method, and the difference lies in whether to introduce a master chamber. In direct pressure detection, it is not advisable to sacrifice the measurement time for measurement accuracy, which has become a bottleneck for improving the production efficiency. The differential pressure detection method has become a significant means of rapid and accurate airtightness detection; however, this method also has limitations such as a relatively long equilibrium time.

In the differential pressure method. Wang et al. [8] studied the differential pressure method and conducted experiments to verify the adaptability of the traditional differential pressure method. Daniels et al. [9] added particle leakage rate analysis on the basis of the differential pressure method. Kagawa et al. verified the influence of temperature recovery imbalance on the accuracy and detection ability of a leak detector [10] and estimated the required temperature recovery time [11]. They then proposed a method for predicting the minimum temperature recovery time [12] and obtained the relationship between different test pressures and volumes and the temperature recovery time [13]. However, they did not consider the traditional differential pressure method, which causes serious differential pressure fluctuations and inaccurate detection owing to environmental pressure fluctuations or electromagnetic noise interference of the sensor.

Based on the pressure difference method, this paper presents some improvement suggestions, establishes a simplified pressure difference model of the asymmetric cavity, analyzes the influence of different simplified parameters on the pressure difference results, and verifies that the model has accurate measurement and short detection time through experiments. The method in this study has a strong automatic detection performance, and the operation requirements of differential pressure airtightness detection technology are relatively simple, which is suitable for detection environments with simple equipment requirements.

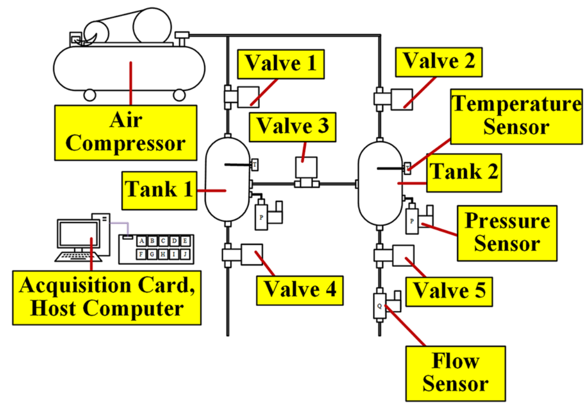

Figure 1 Schematic diagram of leakage measurement by differential pressure method

2 Asymmetric Differential Pressure Method

2.1 Detection Steps of Differential Pressure Method

The airtightness detection method of the differential pressure method mainly refers to the air pressure comparison between the master cavity and tested cavity through a specific structure. If the air pressure of the master cavity and tested cavity is balanced, it indicates that the tested body is in a good airtight state. A pressure difference between the master cavity and tested cavity indicates that the tested cavity has leaked. A structural diagram of the differential-pressure detection method is shown in Figure 1.

In this method, the air compressor fills high-pressure gas in air tank 1 (representing the master cavity without leakage) and air tank 2 (representing the tested cavity with leakage) simultaneously. If the detected workpiece does not leak, the differential pressure sensor maintains a balanced state, whereas if the detected workpiece leaks, the air pressure in the workpiece measurement chamber changes, causing the differential pressure sensor to lose balance.

Air valves 1 and 2 represent the on-off valves of the air tank and air compressor, respectively. Air valve 3 was connected to the two air tanks. Air valves 4 and 5 were used for the exhaust in the experiment, a flow sensor was used for calibration to detect leakage, and temperature and pressure sensors were used to detect the gas state inside the air tank. All the sensors and solenoid valves were controlled using an acquisition card and an upper computer.

The specific test steps are as follows:

(1) Charging both chambers simultaneously: Open the air compressor and valves 1 and 2 to keep the pressure filled into the cavity consistent with the master

pressure of tank 1, which was used for the master chamber, and tank 2, which was used for the test chamber.

(2) Balancing the pressure of the two air tanks: close valves 1 and 2 and open valve 3 to balance the pressure in the master tank and tested tank.
(3) Detection step: Read the change in the pressure difference at both ends of the differential pressure sensor, which is caused by the leakage of the tested tank.
(4) Judgment: The read pressure difference is judged according to the preset value to determine whether the tightness of the tested tank is qualified.

For each charging and testing, the pressures of the two chambers should exhibit the following trend: First, a large amount of air is rapidly poured into the air tank during charging to increase the internal pressure until charging is stopped. In the balance and measurement stage, if the air tank is well sealed, the two chambers are affected by cooling the air tank and reducing the thermal movement of the internal air molecules, leading to a reduction in the pressure in the gas tank. If there is leakage in the gas tank, the total amount of air in the gas tank is reduced, and the pressure in the gas tank is reduced after some air is leaked. In the discharging stage, it can be regarded as a sharp increase in the air leakage and a rapid decrease in the pressure in the gas tank.

2.2 Charging Process and Measurement Process

During charging, the gas in the master chamber is regarded as ideal, and the pressure change in the master chamber is determined by the ideal gas state equation. After differentiating the ideal gas state equation, it can be obtained that:

$$\frac{\mathrm{d}P_{\mathrm{m}}}{\mathrm{d}t}=\frac{P_{\mathrm{m}}}{T_{\mathrm{m}}}\frac{\mathrm{d}T_{\mathrm{m}}}{\mathrm{d}t}+\frac{RT_{\mathrm{m}}}{V_{\mathrm{m}}}G_{\mathrm{im}}, \tag{1}$$

where P_{m} represents the pressure in the master tank, T_{m} represents the temperature in the master tank,V_{m} represents the volume of the master tank, and G_{im} represents the charging flow rate in the master tank.

For the tested chamber, Eq. (2) can be obtained according to the energy conservation and ideal gas state equation. The difference is that there is also mass exchange G_{ew} caused by the leakage of the chamber during charging.

$$\frac{\mathrm{d}P_{\mathrm{w}}}{\mathrm{d}t}=\frac{P_{\mathrm{w}}}{T_{\mathrm{w}}}\frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t}+\frac{RT_{\mathrm{w}}}{V_{\mathrm{w}}}(G_{\mathrm{iw}}-G_{\mathrm{ew}}), \tag{2}$$

where P_{w} represents the pressure in the tested tank, T_{w} represents the temperature in the tested tank,V_{w} represents the volume of the tank, and G_{iw} represents the charging flow rate in the tested tank.

Considering that the leakage mass flow is less than the charging mass flow, the influence of leakage can be ignored in the charging stage. Thus, Eqs. (1) and (2) can be simplified into the following equation:

$$\frac{\mathrm{d}P_{\mathrm{w}}}{\mathrm{d}t}=\frac{P_{\mathrm{w}}}{T_{\mathrm{w}}}\frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t}+\frac{RT_{\mathrm{w}}}{V_{\mathrm{w}}}G_{\mathrm{iw}}. \tag{3}$$

During the measurement, the air source interrupted the charging to the tested chamber and master chamber, and the two chambers were isolated from each other. At this stage, the master cavity only undergoes heat exchange with the environment, whereas the tested cavity undergoes heat exchange with the environment, and the quality is reduced owing to leakage.

For the master cavity, taking $G_{\mathrm{im}}=0$ in charging Eq. (1), the following equation of state for the measurement process can be obtained, as shown in Eq. (4).

$$\frac{\mathrm{d}P_{\mathrm{m}}}{\mathrm{d}t}=\frac{P_{\mathrm{m}}}{T_{\mathrm{m}}}\frac{\mathrm{d}T_{\mathrm{m}}}{\mathrm{d}t}. \tag{4}$$

For the tested cavity, taking $G_{\mathrm{iw}}=0$ in the charging Eq. (2), the following equation of state for the measurement process can be obtained, as shown in Eq. (5).

$$\frac{\mathrm{d}P_{\mathrm{w}}}{\mathrm{d}t}=\frac{P_{\mathrm{w}}}{T_{\mathrm{w}}}\frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t}-\frac{RT_{\mathrm{w}}}{V_{\mathrm{w}}}G_{\mathrm{ew}}. \tag{5}$$

According to Eqs. (4) and (5), the relationship between the differential pressure and leakage can be obtained as shown in Eq. (6).

$$\frac{\mathrm{d}\Delta P}{\mathrm{d}t}=\frac{P_{\mathrm{w}}}{T_{\mathrm{w}}}\frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t}-\frac{RT_{\mathrm{w}}}{V_{\mathrm{w}}}G_{\mathrm{ew}}-\frac{P_{\mathrm{m}}}{T_{\mathrm{m}}}\frac{\mathrm{d}T_{\mathrm{m}}}{\mathrm{d}t}. \tag{6}$$

Theoretically, when the equilibrium time is sufficiently long, the differential of T_{w} and T_{m} is equal to zero, and Eq. (6) can be simplified as follows:

$$\frac{\mathrm{d}\Delta P}{\mathrm{d}t}=-\frac{RT_{\mathrm{w}}}{V_{\mathrm{w}}}G_{\mathrm{ew}}. \tag{7}$$

That is,

$$G_{\mathrm{ew}}=-\frac{V_{\mathrm{w}}\mathrm{d}\Delta P}{RT_{\mathrm{w}}\mathrm{d}t}. \tag{8}$$

2.3 Pressure Difference Substitute Equation

In the actual measurement process, because the pressure measurement inevitably produces measurement fluctuations, resulting in large fluctuations in the differential of the pressure, affecting the measurement results and prolonging the measurement time, this section analyzes the substitute equation of the pressure difference from the perspective of the mechanism and calculates the leakage through the substitute equation, which can obtain the results quickly and accurately. The differential pressure between the tested chamber and master chamber satisfies Eq. (9).

$$\Delta P = P_{\mathrm{w}} - P_{\mathrm{m}}. \tag{9}$$

To solve the expression of ΔP, it can be completed in two steps: first, the differential pressure of the leak-free tank is analyzed, and then the leakage differential pressure is superimposed. The following expression is adopted:

$$\Delta P = \Delta P_T + \Delta P_L. \tag{10}$$

When the tank is qualified, $G_{\mathrm{ew}} = 0$. It is then introduced in Eqs. (9) and (10), as shown in Eq. (11).

$$\frac{\mathrm{d}P_{\mathrm{w}}}{\mathrm{d}t} = \frac{Rh_{\mathrm{w}}S_{\mathrm{w}}(T_a - T_{\mathrm{w}})}{C_v V_{\mathrm{w}}}. \tag{11}$$

Ideal gas equation of state $P_{\mathrm{w}} = \rho_{\mathrm{w}} R T_{\mathrm{w}}$. After replacing T_{w}, we introduce it into Eq. (11) and sort it as follows:

$$\frac{\mathrm{d}P_{\mathrm{w}}}{\mathrm{d}t} + \frac{h_{\mathrm{w}}S_{\mathrm{w}}}{C_v V_{\mathrm{w}} \rho_{\mathrm{w}}} P_{\mathrm{w}} - \frac{Rh_{\mathrm{w}}S_{\mathrm{w}}}{C_v V_{\mathrm{w}}} T_a = 0, \tag{12}$$

where ρ_{w} is the density of the compressed air in the tested chamber. Eq. (12) is the non-homogeneous first-order differential equation of the tested cavity pressure, and the solution to the equation is

$$P_{\mathrm{w}} = \rho_{\mathrm{w}} R (T_0 - T_a) \exp\left(-\frac{h_{\mathrm{w}}S_{\mathrm{w}}}{C_v V_{\mathrm{w}} \rho_{\mathrm{w}}} t\right) + \rho_{\mathrm{w}} R T_a. \tag{13}$$

After replacing each constant parameter with a parameter such as Eq. (14), it obtains $P_{\mathrm{w}} = Ae^{-Bt} + C$, where the boundary condition is $P_{\mathrm{w}}(0) = \rho_{\mathrm{w}} R T_0$.

$$A = \rho_{\mathrm{w}} R (T_0 - T_a),\ B = \frac{h_{\mathrm{w}}S_{\mathrm{w}}}{C_v V_{\mathrm{w}} \rho_{\mathrm{w}}},\ C = \rho_{\mathrm{w}} R T_a, \tag{14}$$

where T_0 is the temperature of the tested chamber when valve 2 is closed, which is the starting temperature of the measurement; T_a is the ambient temperature, which is the final temperature of the tested cavity. Subsequently, the two temperatures satisfy the following relationship:

$$P_s = \rho_{\mathrm{w}} R T_0, \tag{15}$$

$$P_\infty = \rho_{\mathrm{w}} R T_a. \tag{16}$$

The pressure change in the test chamber is the difference between the current pressure value and initial pressure value, and the initial pressure is the value P_s at the end of the inflation balance. By substituting Eq. (13) into Eq. (9), the following expression can be obtained:

$$\Delta P_T = \rho_{\mathrm{w}} R (T_0 - T_a) \exp\left(-\frac{h_{\mathrm{w}}S_{\mathrm{w}}}{C_v V_{\mathrm{w}} \rho_{\mathrm{w}}} t\right) + \rho_{\mathrm{w}} R T_a - P_s. \tag{17}$$

The initial pressure and initial temperature satisfy the ideal gas equation of state

$$\Delta P_T = \rho_{\mathrm{w}} R (T_0 - T_a) \exp\left(-\frac{h_{\mathrm{w}}S_{\mathrm{w}}}{C_v V_{\mathrm{w}} \rho_{\mathrm{w}}} t\right) - \rho_{\mathrm{w}} R (T_0 - T_a). \tag{18}$$

After replacing the temperature value with Eqs. (15) and (16), we can deduce the following:

$$\Delta P_T = (P_s - P_\infty) \exp\left(-\frac{h_{\mathrm{w}}S_{\mathrm{w}}}{C_v V_{\mathrm{w}} \rho_{\mathrm{w}}} t\right) - (P_s - P_\infty). \tag{19}$$

Therefore, if the tank has no leakage, the differential pressure after sealing should be Eq. (20), which is an exponential function with a constant parameter.

$$\Delta P_T = \alpha e^{-\beta t} - \alpha, \tag{20}$$

where,

$$\alpha = P_s - P_\infty = \rho_{\mathrm{w}} R (T_0 - T_a), \tag{21}$$

$$\beta = \frac{h_{\mathrm{w}}S_{\mathrm{w}}}{C_v V_{\mathrm{w}} \rho_{\mathrm{w}}}. \tag{22}$$

Consider that the leakage mass flow G_{ew} is very small and has a slight impact on the cavity pressure; it can be approximately regarded as a fixed value, and the change in differential pressure caused by leakage is linear and meets the following requirements:

$$\Delta P_L = -\frac{R\theta_{\mathrm{w}} G_{\mathrm{ew}}}{V_{\mathrm{w}}} t. \tag{23}$$

By the superposition of Eqs. (20) and (23), the expression of the variation of the differential pressure with time under leakage can be obtained, as shown in Eq. (24), in which the linear parameter is the differential pressure component caused by leakage, and the exponential parameter is the differential pressure caused by temperature recovery.

$$\Delta P = \Delta P_T + \Delta P_L = \alpha e^{-\beta t} - \lambda t - \alpha, \tag{24}$$

where, $\lambda = \frac{RT_{\mathrm{w}} G_{\mathrm{ew}}}{V_{\mathrm{w}}}$.

Thus, the parameters can be identified according to the collected pressure value for the leakage calculation to avoid the influence of a large pressure differential on the measurement results.

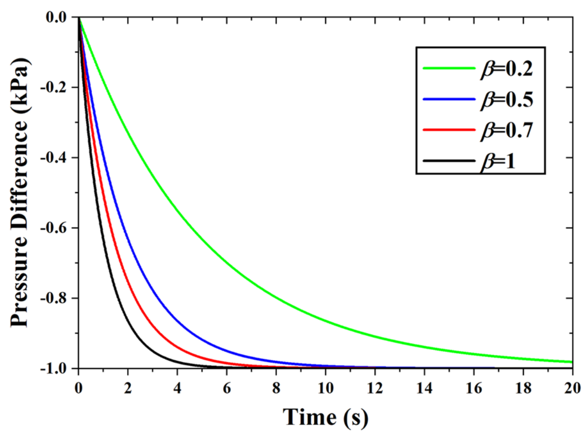

Figure 2 Relationship of β and pressure difference without leakage

3 Simulation of Asymmetric Differential Pressure Method

To study the influence of various parameters in the pressure difference substitute equation on the leakage calculation results, simulations were performed using MATLAB software. In Eq. (24), when α is set to 1 kPa and λ is 0, the simulation results of pressure difference and time different from β are shown in Figure 2.

From Figure 2, with the increase in β, pressure difference decreases faster and the stabilization time is shorter, indicating that the heat exchange capacity of the tested cavity is enhanced. The pressure difference drops sharply before 10 s, and finally reaches a stable value of -1 kPa for different β values. According to Eq. (22), the larger the heat transfer rate h_{w} and heat dissipation area S_{w} of the tank, the larger the β, which indicates a stronger heat exchange capacity. After setting the heat balance time constant as t_h, which represents the time required for the internal energy of the air in the tank to be transferred to the absolute-zero environment, the following relationships exist:

$$T_h = \frac{1}{\beta} = \frac{C_v V_{\mathrm{w}} \rho_{\mathrm{w}}}{h_{\mathrm{w}} S_{\mathrm{w}}}. \tag{25}$$

It can be observed from the equation that the heat balance time is directly proportional to the volume and inversely proportional to the heat transfer material coefficient and heat transfer area. When the measured volume was large, the heat-balance time was prolonged. When a material with excellent heat transfer is used and the heat transfer area is increased, the heat balance time is also reduced. When the gas tank was determined, the balance time and β value were independent of the other parameters.

The relationship among β and pressure difference was explored. In the case of a leakage, in Eq. (24), when α is 1 kPa and λ is 1 kPa, the simulation results for pressure difference and time for different β values are shown in Figure 3. It can be observed that β has a slight relationship with the leakage representative parameter λ. At the beginning of the measurement, the pressure drops with a large β were larger than those with a low β. However, the pressure drop curves of different β values tend to coincide after approximately 10 s. At this time, if there is no leakage, it can be seen from the comparison with Figure 3 that the measurement is stable after 10 s, indicating that after the measurement is stable, different values of β have no impact on the accuracy of the leakage detection, but only on the measurement time.

The exponential parameter α represents the difference among the initial pressure and p_0 and final pressure p_∞. When there is no leakage and a gas tank with a general heat transfer effect is selected, when λ is 0 and β is 0.5, the simulation results of pressure difference and time for different values of α are as shown in Figure 4.

It can be observed that the overall trend of different α is to sharply reduce for a period of time, and then slow down the slope until it tends to α value. When λ and β are determined, the sharp reduction time and slowdown time are the same, indicating that the measured equilibrium time is independent of the α value, which means that the measured equilibrium time is independent of the difference among the initial pressure and final pressure. For example, in this simulation example, the α is taken between 100 kPa and 2000 kPa, and the equilibrium time is 10 to 12 s. Simultaneously, with the increase of α, the pressure difference decreases with a large slope, indicating that for the non-leakage chamber, the temperature after inflation balance and ambient temperature have a

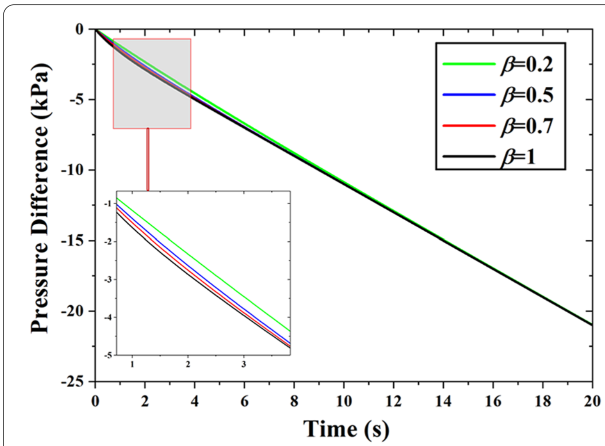

Figure 3 Relationship of β and pressure difference with leakage

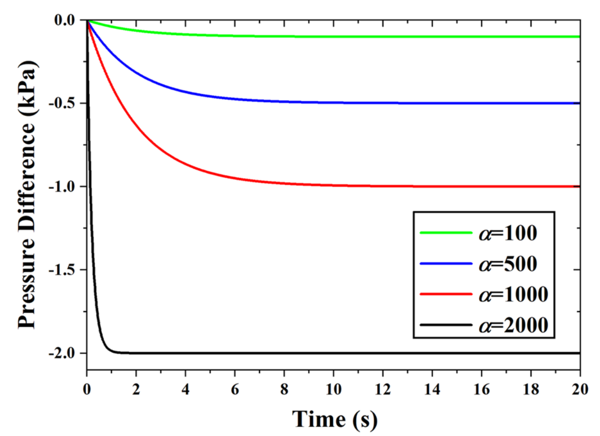

Figure 4 Relationship of α and pressure difference without leakage

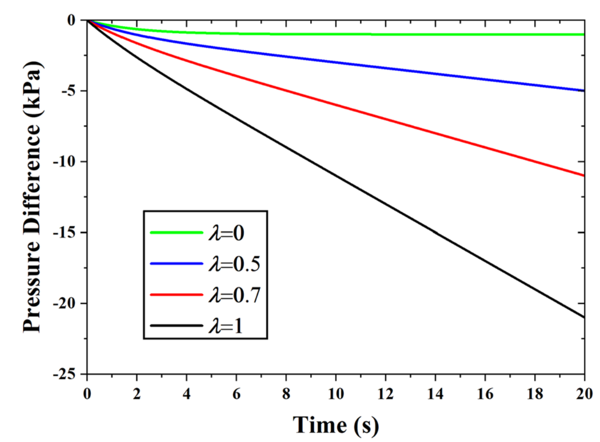

Figure 6 Relationship of λ and pressure difference

severe impact on the measured pressure drop, which has a direct impact on the calculation of the leakage, but has no impact on the measurement time.

When there is a leakage and exploring the influence of pressure difference of different α, the parameter λ is set to 1 kPa and β is 0.5. The simulation results of pressure difference and the time of different α are shown in Figure 5.

As shown in Figure 5, the pressure difference of different α values tends to decrease, and the slope hardly changes with time. With an increase in α, the slope of the pressure drop increased continuously. Owing to the effect of the leakage, the pressure in the chamber decreased until the leakage ended, and the pressure in the chamber reached the atmospheric pressure.

Thus, α is not a characteristic parameter of the tank but a process variable related to the detection process. When different detection pressures were applied, the values changed significantly. This characteristic increases the difficulty of identification during actual measurements. To ensure identification accuracy, the tank model β value was first identified, and α value was further determined.

To determine the influence of the leakage parameters on the pressure drop, it is necessary to fix the inflation detection process variable α and tank characteristics variable β. When α is 1 kPa and β is 0.5, the simulation results of pressure difference with different λ at each time are as shown in Figure 6.

This simulation compared the relationship among the pressure difference and time when λ ranged from 0 to 1. It can be observed that when λ is 0, the pressure difference first decreases to approximately 4 s, and then tends to be stable at − 1 kPa. When λ is greater than 0, the overall trend of the pressure difference always decreases and there is no stable value. With the increase in λ, the decreasing slope of the pressure difference was also steep. λ's derivation equation includes not only the volume of the tested tank but also the leakage. The identification process should be analyzed according to different tanks and leakage conditions.

Therefore, β is relatively stable during the identification process. When the initial pressure is fixed, this value is only related to the tank itself, such as the tank volume, heat-transfer material, and heat-transfer area. Therefore, this value is easy to identify. The empirical value measured in the past or before delivery can be selected and used as the characteristic parameter of the tank to characterize its heat exchange capacity. The value of α was sensitive to the charging process. There is no empirical value for reference, and it cannot be used as a characteristic parameter of the tested tank. This should be identified after β. For the leakage parameters, λ is not only related to the gas tank itself, but is also related to the actual leakage, which should be identified.

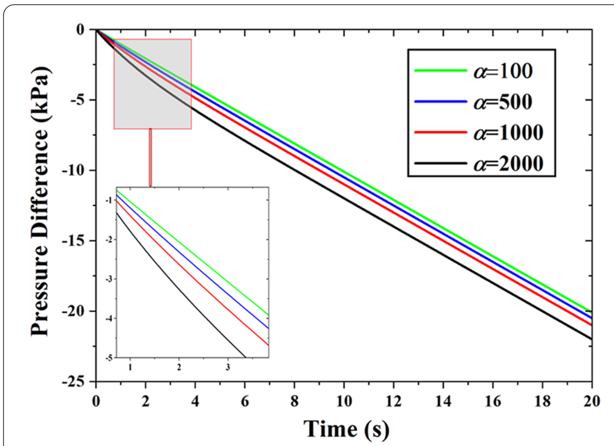

Figure 5 Relationship of α and pressure difference with leakage

4 Experiment of Asymmetric Differential Pressure Method

To further test the effectiveness of the pressure difference substitute equation proposed above for normal tank types, the differential pressure signals during charging and measurement were collected through the data acquisition card for data analysis and identification.

4.1 Introduction of Experimental Equipment

The system used in the experiment is illustrated in Figure 7. It uses an air compressor, air tank, flow sensor, pressure sensor, temperature sensor, acquisition equipment, and upper computer and uses a flow proportional valve to provide leakage. Among them, a 3 L tank (tank 2) was used for the gas tank to be tested, a 20 L tank (tank 1) was used for the master gas tank, an HFT-800 sensor provided by ECOSO company was used for the flow sensor, platinum wire in the range of 0 to 50 °C was used as the thermistor for the temperature sensor, and the corresponding resistance value was collected with the bridge and converted into a voltage signal. The voltage signal of each sensor was calculated as the actual physical value in the upper computer using the acquisition board USB6001 of the NI company. The proportional valve uses the FESTO-MYPE series three-position five-way voltage-control valve. The valve has a position control valve core that converts the analog input signal into the corresponding opening size of the valve output port. The pressure sensor used was the PSE560 series of the SMC company. The tank model selected for the experiment was small for daily use, which is highly representative.

4.2 Experiment and Data Processing

During the experiment, the valve between the air tank and air compressor was first opened for charging, and then the valve connecting the two air tanks was opened to balance the pressure in the two air tanks for a while and then closed. The measurement results can be used for the leakage calculation.

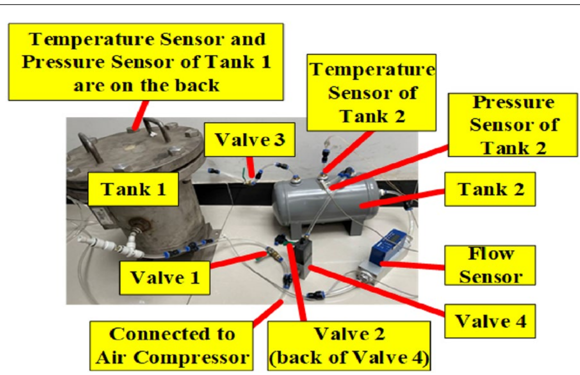

Figure 7 Experiment picture

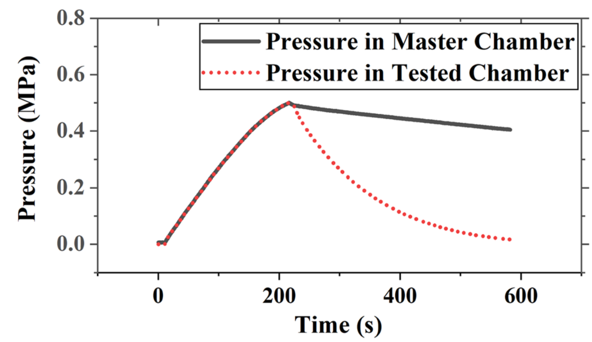

Figure 8 Pressure variation of two chambers with time

To more accurately represent the measurement results and suppress the influence of the random error, the original pressure data are processed by sliding smoothing in the process of data analysis; that is, the original pressure non-stationary data are regarded as nearly stable in appropriate sections and part averaged to reduce the random fluctuation caused by random error. In this manner, continuous local averaging between sections along the full-length data can obtain smoother measurement results and filter out the random error of frequent fluctuations.

Least squares fitting was used in the fitting process. The least-squares method minimizes the variance between sample point y and function $f(x)$ by optimizing function $f(x)$, which is expressed as $\min y - f(x)_2$. The parameters of the function can be easily identified using the least squares method. In this experiment, the smoothed data were fitted using least squares, and α, β, and λ were determined. Finally, after replacing the differential pressure affected by the temperature, the leakage value was consistent with the leakage of the actual tank.

4.3 Cavity Leakage Detection Results

The 3 L gas tank was used as the gas tank to be tested, and the collected field data were pretreated with sliding smoothing, as shown in Figures 8 and 9. In the charging stage, because the maximum amount was much greater than the leakage, the pressure of the two chambers increased synchronously. After reaching approximately 0.5 MPa at 200 s, the air source was closed, and the valve between the two chambers was opened to balance for a period of time. The pressure of the tested chamber decreased sharply owing to leakage, whereas the pressure of the master chamber decreased slowly owing to

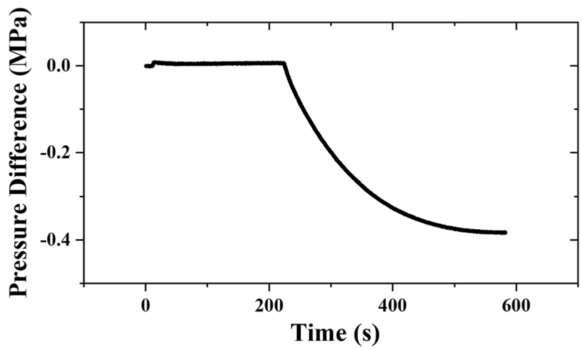

Figure 9 Variation of pressure difference with time

Table 1 Parameter fitting results

α	*β*	*λ*
4.667	0.008115	0.001567

Table 2 Parameter fitting effect

SSE	R-square	RMSE
0.4808	0.9996	0.02119

heat dissipation. This makes the differential pressure have no obvious amplitude in the charging phase but reduce to − 0.4 MPa in the measurement phase.

The pressure difference in the measurement stage was selected separately for exponential function fitting. Within the 95% confidence bounds, it was calculated as shown in Table 1.

The goodness of fit was obtained as follows in Table 2.

In the charging stage, the temperature first increased and then decreased slowly, which was due to the rapid compression of air in the tank during charging and the increase in molecular heat movement, resulting in an increase in temperature. With the slowdown of charging, the heat-transfer system of the tank begins to dissipate heat to the environment, resulting in a decrease in temperature in the later stage of the inflation stage. During the measurement stage, the temperature continued to decrease owing to the leakage. The temperature characteristics of the two stages are listed in Table 3.

Comparing the leakage calculation between the conventional method and the substitute equation method, it can be observed in Figure 10 that the fitting result has a good effect and can converge to the correct leakage interval without fluctuation. In the early stage of

Table 3 Temperature characteristic data of two stages (℃)

	Charging stage	Measurement stage
Maximum value	25.67	25.48
Average value	25.55	25.26
Minimum value	25.43	25.03

measurement, the calculated value of the low leakage is approximately 7.5 L/min, whereas the leakage calculated by the differential pressure method is approximately 9.5 L/min, and there is a maximum oscillation deviation of 0.5 L/min during the measurement process.

In Figure 10, it can be observed from the experiment that using the differential pressure substitute equation to calculate the leakage can obtain a more accurate value without large vibrations, and some parameters in the equation can be obtained from experience. Additionally, some parameters can be obtained by controlling the charging or measurement methods, which have high derivability.

5 Conclusions

To solve the problem of pneumatic leakage detection, a differential pressure fitting method was proposed in this study. The traditional differential pressure method mainly compares the air pressure between the master chamber and test chamber through a specific structure. In the traditional method, when the pressure sensor has low accuracy or the interference in the environment is large, the collected pressure differential data fluctuates, which cannot respond well to the leakage. The remainder of this paper was organized as follows.

(1) In this study, the pressure difference was fitted to an exponential equation to replace the differential calculation of the pressure difference in conventional leakage detection. It has the characteristics of small fluctuations, intuitive measurement, and a fast measurement speed. In the exponential equation, the characteristic parameters of the chamber, measurement process parameter, and leakage characteristic parameter affect the value of the pressure difference in the substitute equation at each time point.

(2) The influence of the three parameters on the pressure difference and the influence of the actual physical parameters affecting the three parameters on the pressure difference were evaluated through

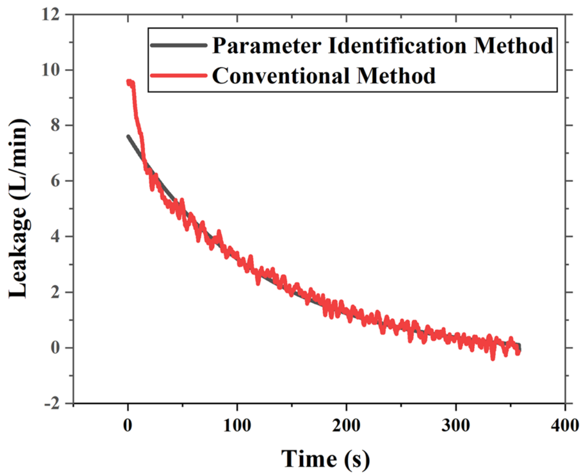

Figure 10 Comparison of leakage calculation between conventional method and substitute equation method

simulation, and a sequence scheme for identifying the parameters was obtained.

(3) The superiority of the pressure difference fitting equation is verified by experiments.

Acknowledgements
Not applicable.

Authors' contributions
YS and XZ were responsible for the conception of the theory, JC was responsible for building the experimental platform and collecting data, YW was responsible for the writing of the article, and the other authors were responsible for the revision of the article. All authors read and approved the final manuscript.

Authors' Information
Yan Shi, born in 1981, is currently a professor at *School of Automation Science and Electrical Engineering, Beihang University, China.*
Jiaqi Chang, born in 1996, is currently a PhD candidate at *School of Automation Science and Electrical Engineering, Beihang University, China.*
Yixuan Wang, born in 1989, is currently a lecturer at *School of Automation Science and Electrical Engineering, Beihang University, China.*
Xuelin Zhao, works currently at *Department of Musculoskeletal tumor, Senior Department of Orthopedics, the Fourth Medical Center of PLA General Hospital, China.*
Qingzhen Zhang is currently an associate professor at *the School of Automation, Science and Electrical Engineering, Beihang University, China.*
Liman Yang is currently an associate professor at *the School of Automation, Science and Electrical Engineering, Beihang University, China.*

Funding
Supported by the Youth Fund of National Natural Science Foundation of China (Grant No. 52105044), National Key R&D Program of China (Grant No. 2019YFC0121702) and National Key R&D Program of China (Grant No. 2019YFC0121703).

Author Details
[1]School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China. [2]Department of Musculoskeletal tumor, The Fourth Medical Center of PLA General Hospital, Beijing 100089, China. [3]Senior Department of Orthopedics, The Fourth Medical Center of PLA General Hospital, Beijing 100089, China.

Received: 15 November 2021 Revised: 21 January 2022 Accepted: 21 February 2022
Published: 27 April 2022

References

[1] Y Shirato, W Ohnishi, H Fujimoto, et al. Controller design of mass flow rate loop for high-precision pneumatic actuator. *16th International Workshop on Advanced Motion Control (AMC)*, 2020.
[2] Cong-Minh Ho, Duc-Thien Tran, Kyoung-Kwan Ahn. Adaptive sliding mode control based nonlinear disturbance observer for active suspension with pneumatic spring. *Journal of Sound and Vibration*, 2021: 509.
[3] D Haraguchi, T Kanno, K Tadano, et al. A pneumatically driven surgical manipulator with a flexible distal joint capable of force sensing. *IEEE/ASME Transactions on Mechatronics*, 2015, 20(6): 2950–2961.
[4] X Liu, J Liu, S Li, Parameter modification model of fluid flow rate for a pneumatically-actuated PDMS membrane microvalve. *2015 International Conference on Fluid Power and Mechatronics (FPM),* 2015: 700–705.
[5] W Tao, X Wang, W Bo, et al. Gas leak location method based on annular ultrasonic sensor array. *2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, 2018.
[6] D Wang, F Zhao, T Wang. The ultrasonic characteristics study of weak gas leakage. *2015 International Conference on Fluid Power and Mechatronics (FPM)*, 2015.
[7] G R Piazzetta, R Flesch, A Pacheco. Leak detection in pressure vessels using ultrasonic techniques. *ASME 2017 Pressure Vessels and Piping Conference*, 2017.
[8] L Zhao, T Wang, P Shi, et al. A novel adaptive leak diagnosis and localization method for infrared image. *International Journal of Innovative Computing Information & Control*, 2012, 8(5B): 3553–3563.
[9] C C Daniels, M J Braun, H A Oravec, et al. Leak rate quantification method for gas pressure seals with controlled pressure differential. *Journal of Spacecraft and Rockets*, 2017, 54(6): 1228–1234.
[10] H L Guntur, M Cai, K Kawashima, et al. Analysis of temperature effect on differential pressure method for air leak detection. *SICE Conference*, 2004.
[11] M Cai, K Kawashima, T Kagawa. Characteristics of leak detection based on differential pressure measurement. *Proceedings of the JFPS International Symposium on Fluid Power*, 2005.
[12] L G Harus, M Cai, K Kawashima, et al. Determination of temperature recovery time in differential-pressure-based air leak detector. *Measurement Science & Technology*, 2006, 17(2): 411–418.
[13] L G Harus, M Cai, K Kawashima, et al. The effect of temperature recovery time on the repeatability of a differential pressure type air leak tester. *Transactions of the Japan Hydraulics & Pneumatics Society*, 2007, 38(4): 54–59.
[14] J Feng Jian, H Zhang, Oil pipeline leak detection and location using double sensors pressure gradient method. *Fifth World Congress on Intelligent Control and Automation*, 2004, 4: 3134–3137.
[15] S Chen, Y Sun, L Wang, et al. Development on dynamic pressure monitoring method and sensor for long pipeline leak detection. *International Pipeline Conference*. 2008.