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

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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,

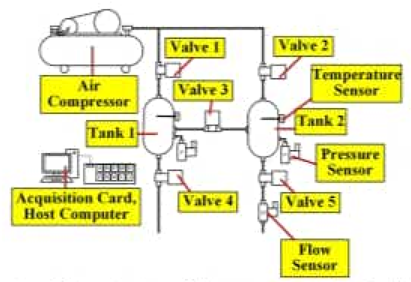

Figure 1 Schematic diagram of leakage measurement by differential pressure method

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:

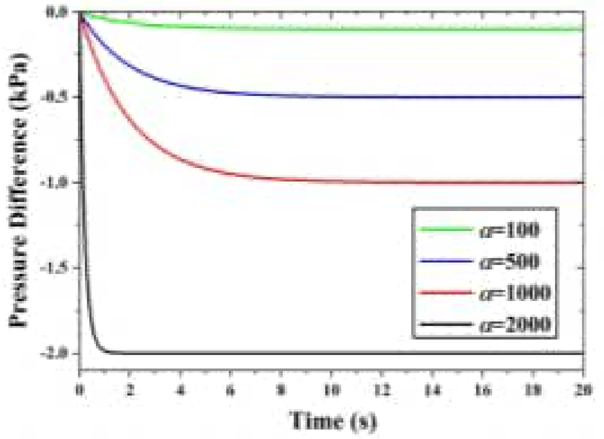

Figure 4 Relationship of α and pressure difference without leakage

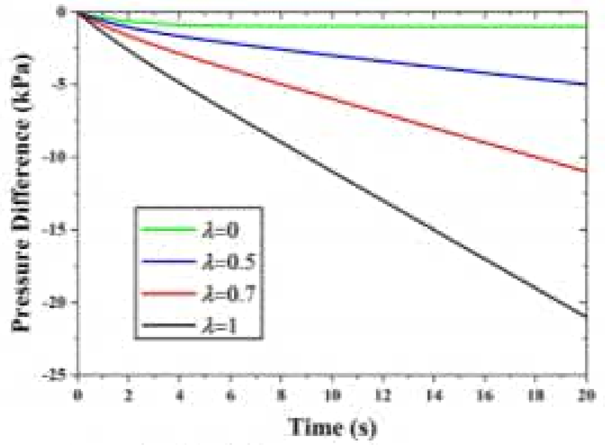

Figure 6 Relationship of λ and pressure difference

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.

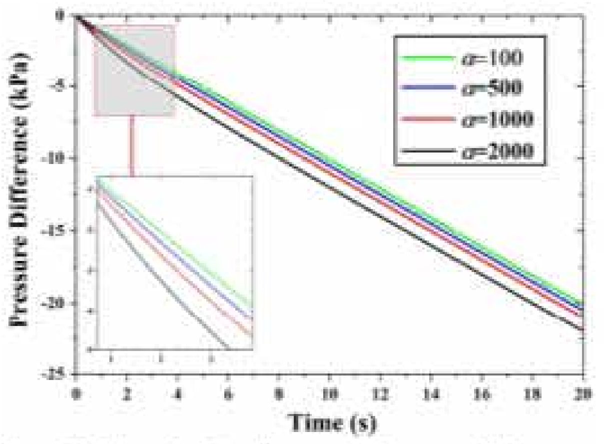

Figure 5 Relationship of α and pressure difference with leakage

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.

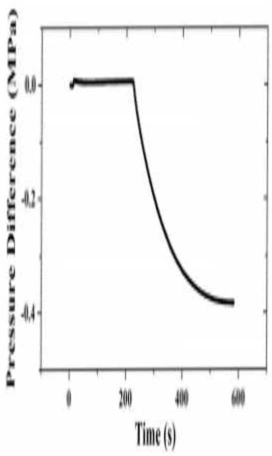

Figure 9 Variation of pressure difference with time

Table 1 Parameter fitting results

α	β	λ
4667	0008115	0001567

Table 2 Parameter fitting effect

SSE	R-square	RMSE
04808	09996	002119

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