DETERMINATION OF CHARACTERISTICS FOR ELECTRICALLY MODULATED PNEUMATIC CONTROL VALVES USING ISOTHERMAL CHAMBERS

Tao Wang[1], Kenji Kawashima[2] and Toshiharu Kagawa[2]

[1] *School of Information Technology, Beijing Institute of Technology, No.5 South Zhongguancun Street, Haidian District, Beijing 100081, China*
[2] *Precision and Intelligence Laboratory, Tokyo Institute of Technology, Nagatsuta-cho 4259, Midori-ku, Yokohama 226-8503, Japan*
wangtaobit@bit.edu.cn, kkawashi@pi.titech.ac.jp, kagawa@pi.titech.ac.jp

Abstract

In the present paper, an automatic test bench is developed for determining the main characteristics of electrically modulated pneumatic control valves using isothermal chambers. In particular, the pressure-flow rate characteristics can be obtained by simply measuring the pressure response inside the isothermal chamber during charge and discharge of air to the chamber. The proposed test bench has a shorter measurement time of only seconds and a lower air consumption as compared to the improved conventional method. Furthermore, the frequency dynamic characteristics with volume load can be measured more accurately owing to the use of an isothermal chamber as a load chamber. The high measurement efficiency and energy savings of the developed test bench are demonstrated herein.

Keywords: pneumatic control valves, flow rate-pressure characteristics, dynamic characteristics, test bench, isothermal chamber

1 Introduction

Pneumatic systems are widely used for precision force and displacement-control devices due to their low cost, clean energy, and non-magnetism, for example (Shearer, 1956; Zalmanzon, 1965). Currently, in semiconductor manufacturing devices such as air spring type isolation apparatuses and positioning systems, pneumatic servo systems have been adopted (Wakui, 2003; Liu et al., 1998; Pu et al., 1989). In pneumatic systems, various electro-pneumatic precision control valves are used as power-transmission and control components.

For high-performance control design, it is important to determine the characteristics of these control valves due to their precision construction and high performance. There are many essential characteristics for a precision control valve, such as the input-output characteristic, the flow rate-pressure characteristic, and the dynamic response, that describe the control valve performance.

The conventional measurement method is referred to as the hydraulic component measurement method (ISO 10770-1, 1998; ISO 10770-2, 1998). For pressure or flow rate precision control valves, since there are two processes with the flow-in and flow-out, supply source and load must be changed in order to achieve complete pressure field measurement. As a result, at present, a long measurement time and a large air consumption are necessary in order to measure these characteristics. Therefore, it would be advantageous to shorten the measurement time and decrease the air consumption. Furthermore, when measuring a dynamic characteristic, the measurement accuracy would become worse due to the fluid temperature change caused by rapid changes in pressure and flow rate. Moreover, the dynamic response of the flow meters largely influences the measurement.

Recently, the authors have proposed the pressure response method to measure flow rate-pressure characteristics of pneumatic solenoid valves in a shorter time using the isothermal chamber (Kawashima et al., 2000; Kawashima et al., 2004). The flow rate can be measured easily and accurately by charging or discharging air into the chamber through the valve, because the isothermal condition is realized by the chamber.

In the present paper, a new test bench is developed for the flow rate-pressure characteristics and the dynamic characteristics of a pneumatic precision control valve using the isothermal chamber. First, the flow rate measurement method based on the pressure response with air charging or discharging in the isothermal chamber is presented. The newly developed test bench is then introduced. Finally, the flow rate-pressure char-

This manuscript was received on 24 April 2007 and was accepted after revision for publication on 30 July 2007

acteristics and the dynamic characteristics of a three-port nozzle-flapper type servo valve are measured using the developed test bench.

2 Flow Rate Measurement using an Isothermal Chamber

The isothermal chamber is a chamber into which copper wire has been stuffed in order to increase the heat transfer area so that an isothermal condition is approached during charge or discharge. The chamber is shown in Fig. 1 (Kawashima, 2000).

The measurement principle of the flow rate of air using the chamber is as follows. The state equation of the air in the chamber is written as

$$PV = WRT \tag{1}$$

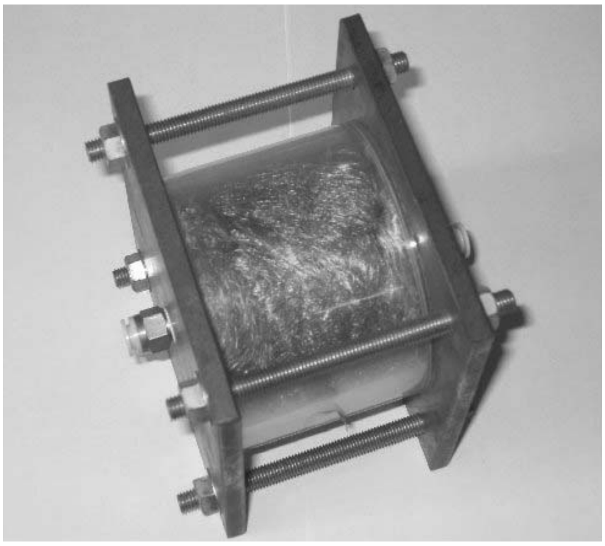


Fig. 1: *Isothermal chamber*

When charging or discharging air into or from the chamber, the pressure, mass flow rate, and temperature response can be obtained by differentiating Eq. 1 with respect to time:

$$V\frac{dP}{dt} = RT\frac{dW}{dt} + WR\frac{dT}{dt} \tag{2}$$

When the diameter of the copper wire is less than 50 μm and the stuffed mass is greater than 300 g/dm^3, because of the large heat capability of the copper wire and because the heat transfer area between the copper wire and air inside the chamber is sufficiently large, the air temperature inside the chamber can be maintained constant during charging or discharging when the pressure response change is less than 100 kPa/s. As a result, the second term of the right-hand side of Eq. 2 becomes zero. Applying $G = dW/dt$, the flow rate G can then be obtained from Eq. 2 as follows:

$$G = \frac{V}{RT}\frac{dP}{dt} \tag{3}$$

From Eq. 3, there is a proportional relationship between the flow rate and the differential pressure. Therefore, the flow rate can be obtained by differentiating the measured pressure response with respect to time.

Transferring the mass flow rate to the volumetric flow rate under the standard condition, the following equation can be obtained.

$$Q = \frac{G}{\rho_0} \tag{4}$$

The flow rate can be calculated from the pressure response without using a flow meter. When air is discharged from the tank, dP/dt is negative, and when air is charged into the tank, dP/dt becomes positive.

3 Development of a Precision Test Bench for the Pneumatic Control Valve

In order to determine the various characteristics for pneumatic control valves precisely and rapidly with less air consumption, a test bench for pneumatic control valves is developed using the above measurement principle. The developed test bench is shown in Fig. 2.

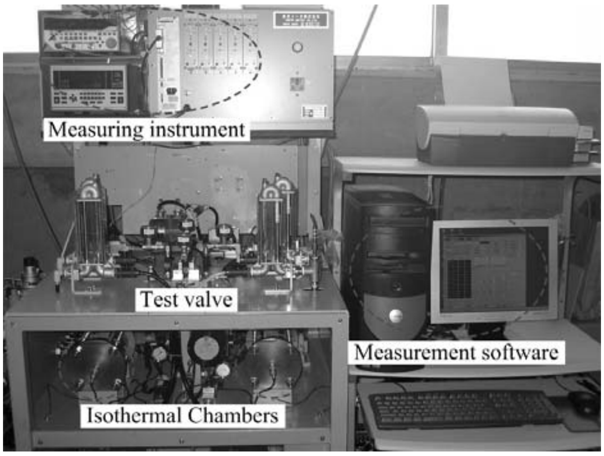


Fig. 2: *A test bench for pneumatic control valves*

The test bench consists primarily of three units: the air supply and process unit, the installation unit, and the control and measurement unit. The details of each unit are as follows:

- The air supply and process unit consists of an air booster, a safety valve, a filter, a buffer tank of 0.038 m^3, and a precision pressure regulator. In order to supply stable and clean air to the measuring devices, since the air pressure varying from 650 ~ 750 kPa is supplied by a compressor, the compressed air is pressurized up to 850 kPa by the booster. The supply pressure is then set at 700 kPa by the precision regulator with the buffer tank. The dust and moisture in the compressed air are removed by three filters.
- The installation unit consists of a test valve mount, isothermal chambers, on-off valves, a precision pressure controller, and pressure, flow rate, and temperature sensors. Installation of test components, control of air flow direction, acquirement of the experimental pressure, flow rate, and temperature signals are carried out by this unit.
- The control and measurement unit consists of a PC,

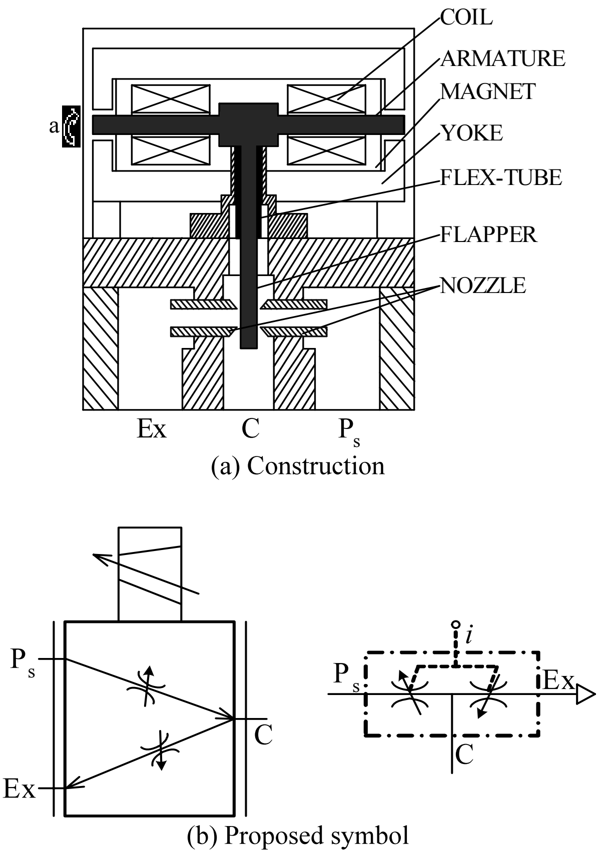
an AD/DA board, a serial signal transform board, and exclusive measurement and control software programmed in the C language. Inputting the signal to test components, controlling the on-off valves, and handling experimental data are carried out by this unit.

Using the developed test bench, pressure output, flow rate output, pressure-flow rate, step response, and frequency response characteristics of various pneumatic control valves can be determined. In addition to these measuring items, leakage flow rate and output stability can also be measured.

The following section will explain in detail the measurement methods of the flow rate-pressure characteristic and frequency response characteristic with volume load for a nozzle-flapper type electro-pneumatic pressure-control valve using the newly developed test bench with isothermal chambers.

4 Tested Valve

As a test valve, a dual-nozzle single-flapper type servo valve is selected to determine its characteristics using the proposed method. Nozzle-flapper type servo valves are widely used in pneumatic systems as precise control components due to their simple structure, high sensitivity, and wide frequency range. Therefore, for a pneumatic servo system to optimize design and performance improvement, it is necessary to investigate the characteristics of their servo valves precisely.



(b) Proposed symbol

Fig. 3: *Contraction and symbol of a three-port nozzle flapper type servo valve (Ps: supply pressure; C: control port; Ex: exhaust port)*

The basic construction and the proposed three-port nozzle-flapper type servo valve are shown in Fig. 3(a) and 3(b), respectively. The armature-flapper is moved by a torque motor consisting of a coil and vertically arranged magnets. The movement of the flapper changes the distance between the flapper and both nozzles. This creates a different area at the inlet and outlet port, thus changing the control pressure P_c at the control port C. The servo valve used in the present experiment, P075-221, is manufactured by the PSC Company. The range of control pressure change is 0 ~ 550 kPa for the rated current of 100 mA and air supply pressure of 550 kPa.

5 Flow Rate-Pressure Characteristic Measurement

5.1 Conventional Method for Determination of Flow Rate Characteristic (Directly-flow Rate-Measured Method)

The conventional measurement method for a three-port nozzle-flapper type valve is shown in Fig. 4. The flow rate characteristics are determined by changing the load (a variable orifice) connected to the downside of the control port of the valve. The flow rate-pressure characteristics between the supply and the control port (flow-in characteristics) are measured by changing the load pressure using the variable orifice (Fig. 4(a)). When measuring the flow rate-pressure characteristics between the control and the exhaust port (flow-out characteristics), we must adjust the load pressure with a regulator, installed on the control side of the valve (Fig. 4(b)). We call this method the directly-flow rate-measured method. Since the flow-in and flow-out characteristics must be measured several times changing the flow rate or the supply pressure, the required measurement time and air consumption are great.

The improved experimental apparatus shown in Fig. 5 is used for the conventional methods. The supply pressure for the servo valve is set by a precision regulator B. A buffer tank C with volume of 10 dm^3 is installed between regulator B and test valve D to stabilize the air pressure. The load pressure is adjusted by an electro-pneumatic converting regulator F, which can be controlled to continually change the pressure in the control side of the test valve by the electric signal from the PC. A dual directional flow meter E is connected between the control side of the valve and E/P regulator F. Therefore, by adjusting the pressure slowly at the control side of the valve with the E/P regulator from the atmosphere to the supply pressure continually, the pressure and flow rate during air in or air out to the valve can be measured simultaneously.

Compared to the conventional method described above, the improved method has the advantages of a simple measurement circuit and automatic measurement.

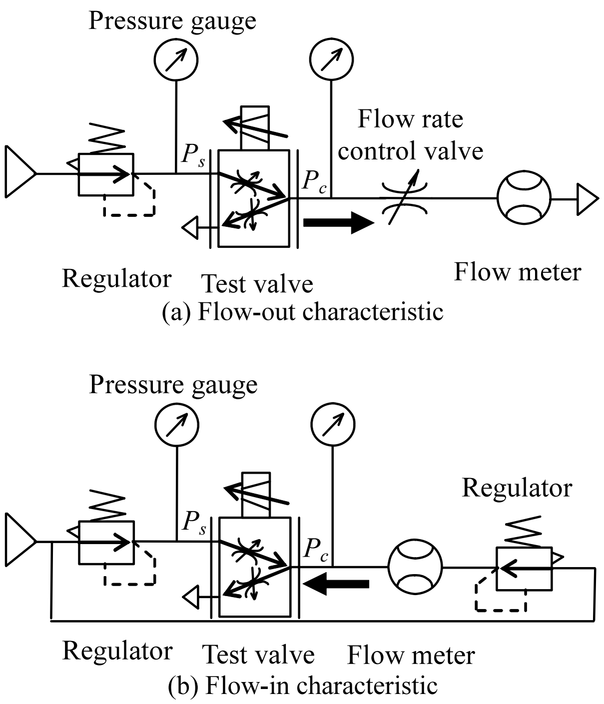


Fig. 4: *Conventional measurement circuit for pressure - flow rate characteristics*

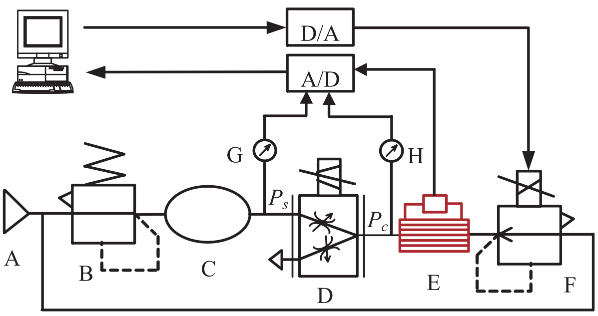


Fig. 5: *Experimental apparatus for P-Q characteristics using a dual directional flow meter (A: Supply; B: Regulator; C: Buffer tank; D: Test valve; E: Dual directional flow meter; F: E/P regulator; G, H: Pressure transducer)*

5.2 Flow Rate-Pressure Characteristic Measurement with the Test Bench

As shown in Fig. 6, an isothermal chamber is connected to the control side of the test valve and to two lager on-off solenoid valves. By controlling two on-off valves, charging air into or discharging air out from the isothermal chamber can be selected. The pressure response is measured and transferred to the PC.

Using Eq. 3, the flow rate from the pressure change in the isothermal chamber can be calculated. Since the air flowing into or out of the chamber is equal to the flow rate through the test valve, and the pressure at the control port is equal to that of the chamber, the flow rate-pressure characteristic can be obtained in a short time during charging or discharging. In order to stabilize the supply pressure, a buffer tank C is installed between the precision regulator and the test valve.

This research focuses on electrically modulated pneumatic servo valves. However, the flow rate characteristics of a pneumatically controlled valve linked to a pilot valve controlled by a nozzle flapper can also be measured with the proposed test bench giving an input signal.

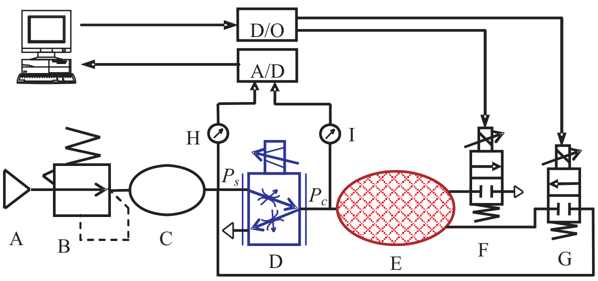


Fig. 6: *Experimental apparatus for flow rate characteristics using an Isothermal Chamber (A: Supply; B: Regulator; C: Buffer tank; D: Test valve; E: Isothermal Chamber; F: Charge valve; G: Discharge valve; H, I: Pressure transducer)*

5.3 Test Procedure

The test procedure is as follows:

- The supply pressure is set to 550 kPa by precision regulator B, and an input current is given to test valve D.
- Shut valve G and open valve F. The pressure in the isothermal chamber then reaches atmospheric pressure. Next, valve F is closed. At this time, the pressure response from the atmosphere to the operating pressure while the air charged into chamber is recorded by pressure transducer I.
- Close valve F and open valve G. The air is charged into the isothermal chamber through valve G. Valve G is then closed. Here, the pressure response is recorded from supply to the operating pressure while the air is discharged from the chamber.
- Smooth the pressure data with a low-pass filter with a cut-off frequency of 50 Hz and calculate the flow rate by differentiating the data and using Eq. 3 while charging and discharging. The flow rate-pressure characteristics of the servo valve between the atmosphere and the supply pressure can be obtained.

5.4 Experimental Results

5.4.1 Static Pressure Output Characteristic

First, the static pressure output characteristic of the test valve is investigated with the port C closed. Varying the input current from 0 to 100 mA by using a triangular waveform with 1/120 Hz, the pressure change of the control pressure with respect to the input current is measured as shown in Fig. 7. From the results, it is determined that the threshold value is approximately 7% of the rated current, and the pressure hysteresis is approximately 2.9 %. From 30 ~ 70 mA there is a higher linearity for applying the control system.

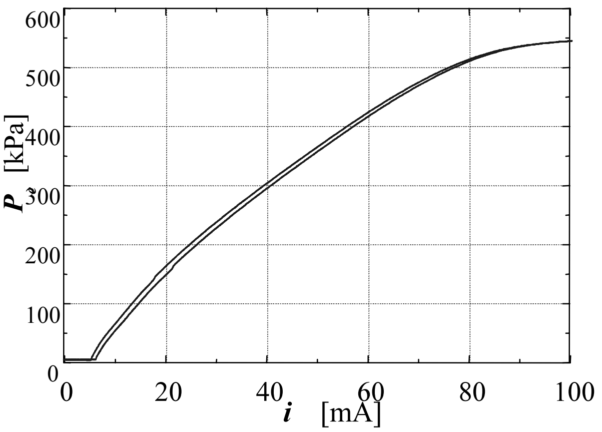


Fig. 7: *Control pressure with respect to input current*

5.4.2 Flow Rate–Pressure Characteristics

The input current is set to 30, 50, 70, and 90 mA, respectively. The volume of the isothermal chamber is 1 dm^3. As shown in Fig. 8, the charge and discharge measurement is achieved within a short time of less than 25 seconds. When using the dual-directional flow meter and the E/P regulator, the input signal was varied using a triangular waveform varying from 0 to 3 V in 120 seconds. The load pressure is set from atmosphere to supply.

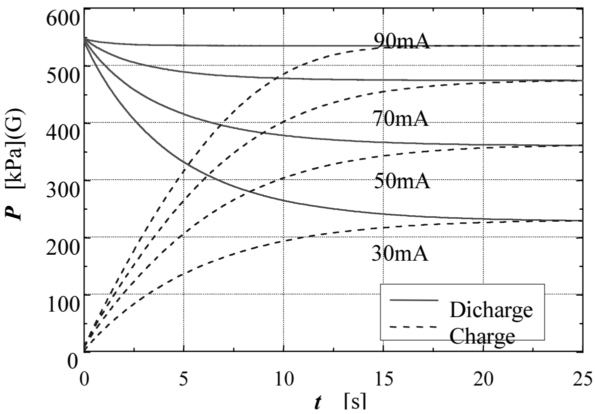


Fig. 8: *Pressure response during charge and discharge*

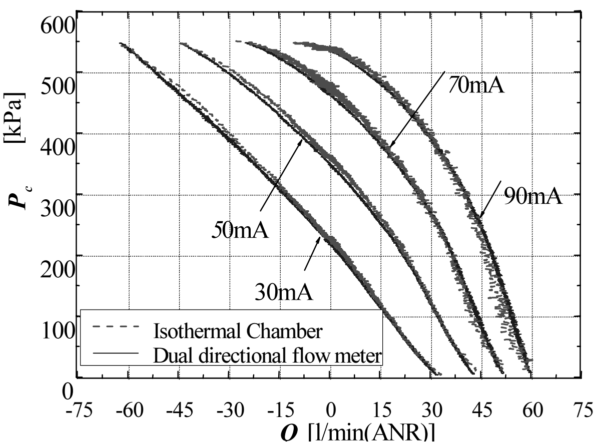


Fig. 9: *Flow rate–pressure characteristics of a three-port nozzle flapper type servo valve*

The results for the flow rate–pressure characteristics are shown in Fig. 9. The results indicate the effectiveness of the proposed method because both methods show good agreement at each setting input current.

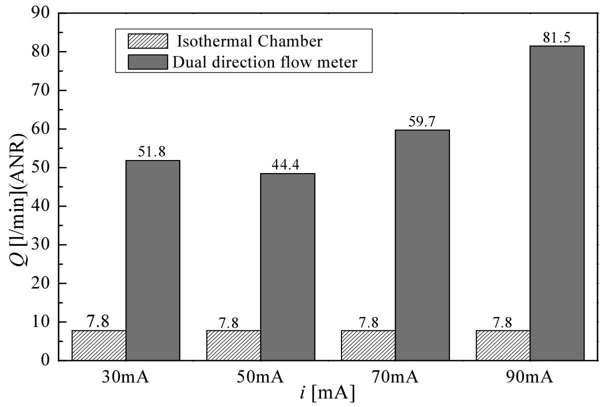


Fig. 10: *Air consumptions using the proposed method and the directly-flow rate-measured method*

Furthermore, air consumptions during the measurement time are compared, and the results are shown in Fig. 10. The air consumption of the proposed method is only 1/5~1/10 of that of the improved conventional measurement method.

6 Frequency Response Characteristics with Volume Load

6.1 Dynamic Model of the Tested Valve

In pneumatic position and force control systems, nozzle-flapper type servo valves are normally used. It is important to determine not only the static but also the dynamic characteristics of the valves for the controller design.

Although the dynamic characteristics of nozzle-flapper type servo valves are governed by the torque motor, the armature-flapper, and the control chamber, the dynamics inside the control chamber dominate the nozzle-flapper type servo valve dynamics at low frequency when the volume of the control chamber is sufficiently large and the temperature is constant (Wang, 2005). Therefore, when an isothermal chamber is used as the control chamber, the transfer function of the above test valve can be written simply as follows:

$$\frac{P(s)}{i(s)} = \frac{K_{sv}}{T_c s + 1} \tag{5}$$

where T_c is the time constant of the pressure response and can be written as follows:

$$T_c = \frac{V}{aRT} \tag{6}$$

where a is the flow rate gain with respect to the control pressure. From the flow rate-pressure characteristics shown in Fig. 9, a can be obtained at a certain operation current by calculating the inclination of the flow rate variation to pressure as follows:

$$a = \frac{\Delta G}{\Delta P_c}\ . \tag{7}$$

6.2 Experimental Apparatus and Results

The test circuit for the determination of the dynamic characteristics is shown in Fig. 11. Valve F and valve G in Fig. 6 are closed. The nozzle flapper valve shown in Section 5 is used for the test. Sinusoidal current with amplitude of 5 mA and a biased input of 50 mA are given to the valve with various frequencies. The pressure response in the chamber can be determined, which can be used as the pressure response at the control side of the test valve. The frequency dynamic characteristic of the pressure response is summarized in the Bode diagram with respect to the amplitude ratio and phase.

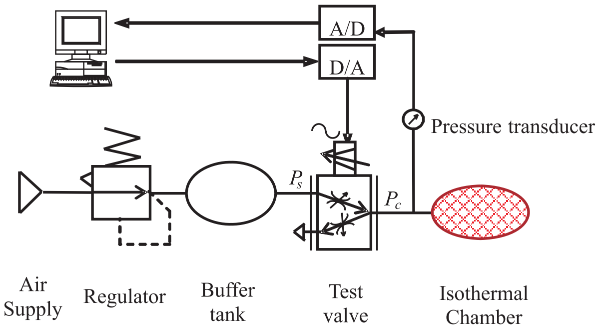


Fig. 11: *Experimental apparatus for frequency response of a test servo valve with a load Isothermal Chamber*

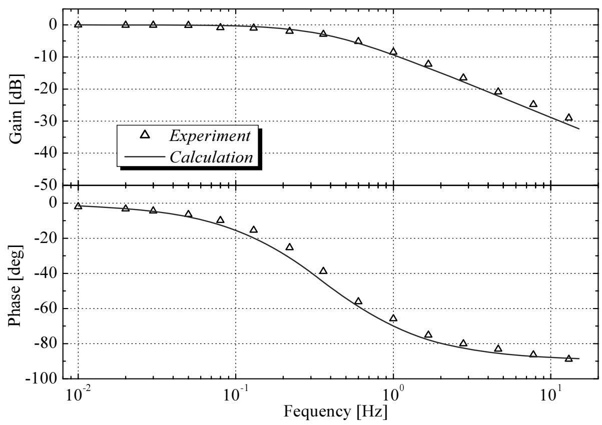


Fig. 12: *Frequency response of the pressure with volume of 0.1 dm^3*

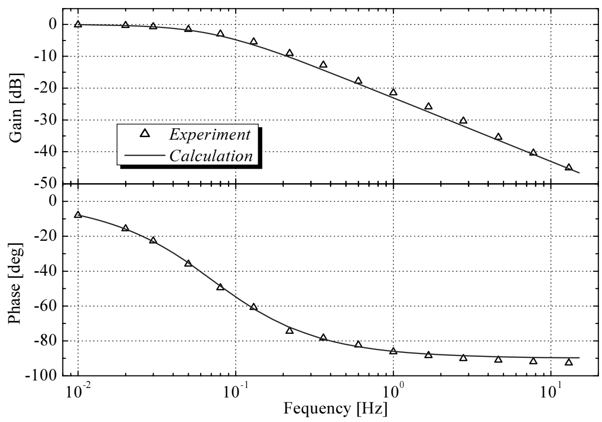


Fig. 13: *Frequency response of the pressure with volume of 0.5 dm^3*

At a nearby operating point with a current of i = 50 mA, the authors obtained $K_{sv} = \Delta P_c / \Delta i$ = 6.56 kPa/mA from the experimental results of the control pressure shown in Fig. 7 and $a = 3.99\times10^{-6}$ (kg/s)/kPa from the experimental results of the flow rate-pressure shown in Fig. 8.

The frequency response can be calculated using Eq. 5. In addition, the frequency response was summarized in a Bode diagram as shown in Fig. 12 and 13. The results indicate that the experimental and calculated results show good agreement for frequency characteristics from 0.01 Hz to 10 Hz for various volumes of 0.1 dm^3 and 0.5 dm^3. Using the isothermal chamber, the dynamic characteristics of control valves can be determined accurately and simply.

7 Conclusions

Using the developed test bench with the isothermal chambers, determination of the flow rate-pressure characteristic was achieved in a short measurement time and with reduced air consumption, while maintaining the precision, as compared with the conventional directly-flow rate-measured method. Moreover, using the test bench, it was possible to measure the frequency dynamic characteristic accurately and simply.

Acknowledgement

The authors are grateful to Tokyo Meter Co., LTD for their support.

Nomenclature

G	mass flow rate	[kg/s]
i	input current	[mA]
K_{sv}	pressure gain	[Pa/mA]
P_a	atmosphere pressure	[Pa]
P_c	control pressure	[Pa]
P_s	supply pressure	[Pa]
Q	volume flow rate for standard conditions	[l/min (ANR)]
R	gas constant	[m^2/s^{2}K]
V	volume of isothermal chamber	[m^3]
W	air mass in isothermal chamber	[kg]
T	temperature	[K]
T_p	time constant of pressure in the isothermal chamber	[s]
t	time	[s]
ρ	air density for standard conditions	[kg/m^3]

References

ISO 10770-1: 1998. Hydraulic Fluid Power – Electrically Modulated Hydraulic Control Valves – Part 1: Test Methods for Four-way Directional Flow Control Valves.

ISO 10770-2: 1998. Hydraulic Fluid Power – Electrically Modulated Hydraulic Control Valves – Part 2: Test Methods for Three-way Directional Flow Control Valves.

Kawashima, K., **Fujita T** and **Kagawa, T.** 2000. Instantaneous Flow Rate Measurement of Ideal Gases. *ASME Journal of Dynamic System,* Vol. 122, pp. 174-178.

Kawashima, K., **Ishii, Y.**, **Funaki, T** and **Kagawa, T.** 2004. Determination of Flow Rate Characteristics of Pneumatic Solenoid Valves Using an Isothermal Chamber. *ASME Journal of Fluids Engineering,* Vol. 126, pp. 273-279.

Liu, S. and **Bobrow, J. E.** 1998. An Analysis of a Pneumatic Servo System and Its Application to a Computer-controlled Robot. *Trans. ASME Ser G: J Dyn Syst Measure Contr,* Vol. 110, pp. 228-235.

Pu, J. and **Weston. R. H.** 1989. A New Generation of Pneumatic Servo for Industrial Robot. *Robotics,* Vol. 7, pp. 17-23.

Shearer, J. E. 1956. Study of Pneumatic Process in the Continuous Control of Motion with Compressed Air-I, II. *Trans. ASME, Feb.*, pp. 233-249.

Wakui, S. 2003. Incline Compensation Control Using an Air-Spring Type Active Isolated Apparatus. *Precision Engineering*, Vol. 27 (2), pp. 170-174.

Wang, T., **Cai, M.**, **Kawashima, K.** and **Kagawa, T.** 2005. Modelling of a Nozzle-flapper type Pneumatic Servo Valve Including the Influence of Flow Force. *International Journal of Fluid Power,* Vol. 6, No. 3, pp. 33-43.

Zalmanzon, L. A. 1965. *Components for Pneumatic Control Instruments*. Pergamon Press.

Tao Wang
Born in December 1971. Received his M. Sc from the Beijing Institute of Technology (China) in 1999 and Ph. D degree from Tokyo Institute of Technology (Japan) in 2006. Now he is working as an associate professor at the Beijing Institute of Technology. His primary research fields are modeling and control of pneumatic servo system and pneumatic components characteristics measurement.

Kenji Kawashima
Born in July 1968. Received his Ph. D degree from the Tokyo Institute of Technology (Japan) in 1997. He is working as an associate professor at the Precision and Intelligence Laboratory of the institute. His primary research interests are robot engineering and fluid measurement and control.

Toshiharu Kagawa
Born in November 1950. Received his M. Sc and Ph. D degree from the Tokyo Institute of Technology in Japan. He is working as a professor at the Precision and Intelligence Laboratory of the institute. His primary research interests are fluid dynamics, fluid measurement and control.