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A new, high precision, quick response pressure regulator for active control of pneumatic vibration isolation tables

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ABSTRACT

Pressure regulators are important elements in pneumatic systems. Relief-type precision pressure regulators are commonly used to control the supply pressure to actively controlled pneumatic vibration isolators.

Herein, a high precision, quick response pneumatic pressure regulator is proposed. This consists of an isothermal chamber, a servo valve, a pressure sensor, a quick response laminar flow sensor (QFS), and a pressure differential sensor (PD sensor) as developed by the authors. Slight changes of pressure in the chamber can be detected by the PD sensor and are fed back to the servo valve to maintain the pressure at a desired value. The performance of this regulator was confirmed experimentally in comparison with one available commercially. The regulator was then applied to the supply pressure regulation of an actively controlled pneumatic vibration isolation table. The superior performance of the regulator is clearly shown in the experimental results, especially in terms of avoiding effects from upstream or downstream disturbances.

1. Introduction

Pneumatic vibration isolators are widely used to isolate precision machinery. The air-springs which are usually employed can support a high pay load using relatively low energy [1]. In turn, these air-springs are often actively controlled by servo valves to attenuate vibrations transmitted through the floor and to suppress vibrations of the table; typical applications are ultra-precision machinery such as scanners and steppers used in semiconductor production [2,3]. Active control achieves high stability and a wide isolated bandwidth. Most of these air-spring systems are controlled using nozzle flapper type pneumatic servo valves which have both quick response and high linearity.

Regulators are essential components of pneumatic systems. In order to control the pressure of flammable gases, where leakage must be prevented, gas governors are used. However, as leakage is acceptable in most other pneumatic systems, relief-type pressure regulators are widely used [4]. In order to control the supply pressure to vibration isolators, standard commercial precision pressure regulators are often used. However, the response of most of these is relatively slow.

For regulators for ultra-precision applications, the need for quick response and accuracy must be addressed. The standard approach to negate the deficiencies of commercially available regulators is to install an accumulator tank between the regulator and the isolator servo valve. However, even this is largely inadequate.

Herein, a new type of pneumatic pressure regulator is proposed which exhibits high precision and quick response. The regulator consists of an isothermal chamber, a spool type servo valve (SP valve), a pressure sensor, a quick response laminar flow sensor (QFS), and a pressure differential sensor (PD sensor) as developed by the authors.

The structure and design of the proposed pressure regulator are explained in Section 2. Performance tests on a fabricated prototype are conducted in Section 3. In Section 4, to evaluate the effectiveness of the regulator, it is applied to the control of the supply pressure to an actively controlled pneumatic vibration isolator. Finally, Section 5 presents some conclusions.

2. Development of a high precision, quick response pressure regulator

2.1. Structure of the proposed regulator

A schematic and photograph of the proposed pressure regulator are shown in Figs. 1 and 2, respectively. It is composed of an SP valve (FESTO MPYE-5-M5-SA), a QFS, an isothermal chamber, a PD sensor

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Nomenclature

A	air-spring area (m^2)
c	damping coefficient (N s/m)
f_c	cut-off frequency (Hz)
G_{in}	input flow rate (kg/s)
G_{out}	output flow rate (kg/s)
k	spring coefficient (N/m)
K_a	acceleration feedback gain (s^2 V/m)
K_{gi}	integral gain for mass flow control (Pa/kg)
K_{NF}	nozzle flapper type servo valve gain (Pa/mA)
K_p	proportional gain for pressure control (kg/(s Pa))
K_v	spool type servo valve gain (kg/(s V))
K_{vc}	gain of voltage/current converter (mA/V)
K_x	proportional gain for displacement control (V/m)
K_{xi}	integral gain for displacement control (V/(m s))
L	slit length (m)
M	mass (kg)
P	pressure (Pa [abs])
P_{ref}	reference pressure (Pa [abs])
P_s	supply pressure (Pa [abs])
R	gas constant (J/(kg K))
T	time constant (s)
T_p	pressure control loop time constant (s)
V	volume (m^3)
V_d	pressure differentiator volume (m^3)
θ	temperature (K)

and a pressure sensor (TOYODA PD-64S500K). Though the SP valve had 5 ports, the valve was used as a 3 port servo valve, i.e. supply, control and exhaust ports. The unused ports were plugged.

The 'Isothermal Chamber' is the result of previous research [5]. This is filled with metal wool which leads to a nearly isothermal state change in the chamber. The isothermal chamber used herein has a volume V of 10×10^{-3} m^3. A QFS is a differential pressure type flow sensor and its dynamic characteristics were calibrated using an "unsteady flow generator" in previous research [6]. The 'PD sensor' measures the pneumatic pressure differential with high precision and a quick response [7]. A schematic and photograph of the PD sensor used in this research are shown in Figs. 3 and 4, respectively. The PD sensor is composed of an isothermal chamber, a cylindrical-shaped slit type flow channel and a diaphragm-type differential pressure sensor. With reference to Fig. 3, when the measured pressure P changes, the air flows through the cylindrical flow channel into the isothermal chamber, and the pressure in the isothermal chamber P_c follows P with a slight lag. By measuring the pressure differential $\Delta P = P - P_c$ Pa, the differentiated value of P can be calculated. The resolution of the PD sensor used in this

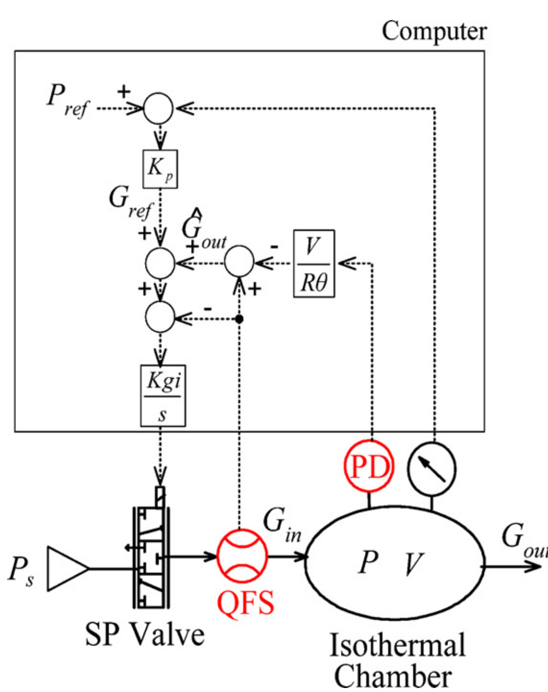

Fig. 1. Regulator schematic.

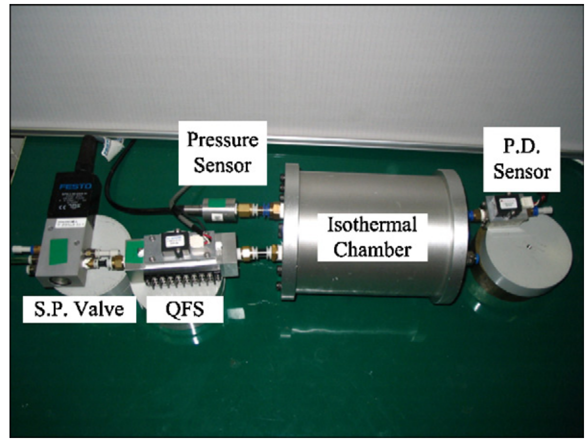

Fig. 2. Photograph of the regulator.

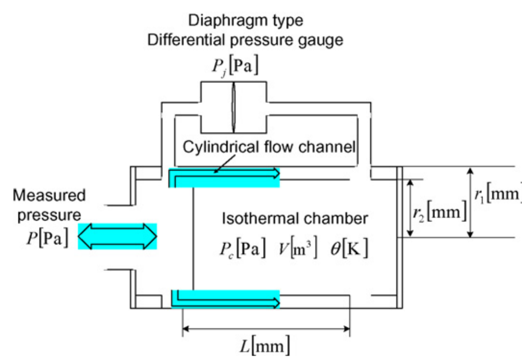

Fig. 3. Schematic of the PD sensor.

Fig. 4. Photograph of the PD sensor.