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MEASUREMENT OF THE PULSATION IN GAS PIPE LINE AND FEASIBILITY EVALUATION OF THE GAS PULSATION DUPLICATING SYSTEM

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ABSTRACT

A purpose of this study is to develop a novel flow meter evaluation system which can realize the same gas pulsation flow characteristics in a lab as in a field, such as a chemical plant or a gas pipe line system. In order to develop this system, this research adopts a an experimental approach using an "Oscillatory flow generator using isothermal chambers" and "Quick and precise pressure regulator". The prototype system developed in this research showed a precise duplicability of a pulsation flow. A present problem in such system is that there have not been any devices having enough performance to evaluate the accuracy of the flow meter under a pressure pulsation condition, although a flow meter usually can be affected by a sudden pressure change. Now, therefore, flow meter tests have to be conducted in the real plant systems. But, these experiments in the real plant system cost time and money. As a result, Industries related to plant systems definitely need a flow meter evaluation system that can produce arbitrary pulsation flow. In order to realize the boundary conditions, a very quick and precise pressure regulating device, which is invented in our former research, is essential. In addition, in the experimental approach, a prototype system was made and the similarity of the pulsating flow to real system was evaluated precisely. The system consists of three main components, an oscillatory flow generator, a quick and precision pressure regulator, and a flow meter. The type of flow meter used in this research is laminar flow type, which is composed of a laminar flow element and a differential pressure gauge. The dynamic characteristics of the flow meter are calibrated by using an "Unsteady flow generator using isothermal chambers" , which can generate arbitrary unsteady flow. The unsteady flow generator was developed in our former research. In conclusion, by these simulation and experimental approaches, the arbitrary gas pulsation duplicating system, containing the pressure regulating devices, are developed and the performance tests are conducted. Our system can be a potential candidate for reducing the cost of flow meter evaluation under a pulsation flow.

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INTRODUCTION

Pressure in the pipeline for the gas changes greatly depending on the conditions of connected other equipments. However, there has not been a device having enough performance to evaluate the accuracy of the flow meter used under such pressure pulsation condition. So, at present, flow meter tests can only be conducted in the real plant systems. These experiments in the real plant system may involve costs. In this research, in order to solve those problems, a new system which can duplicate arbitrary gas pulsation flow is proposed, using a oscillatory gas flow generator and a quick and precision pressure regulator. The arbitrary gas pulsation duplicating system is fabricated and the performance tests are conducted. The possibility of realizing the arbitrary gas pulsation duplicating system is evaluated.

OSCILLATORY GAS FLOW GENERATOR

The oscillatory gas flow is generated using an isothermal chamber, two spool type servo valves and an ejector as shown in Fig.1. Here, ΔG_f is the forward part of the amplitude of the oscillatory flow and ΔGr is the reverse part of the oscillatory flow, respectively. Only three ports are actually used though the servo valve which used in this generator is possessed by five ports. When port1 and port2 are connected, this generator can generate the forward flow, and when port2 and port3 are connected, the reverse flow can be generated. At first, the forward flow is generated as follows:

The state equation for compressible fluids in a chamber can be written as

$$PV = WR\theta \tag{1}$$

The following equation can be derived by differentiating Eq.(1), if the chamber volume is constant:

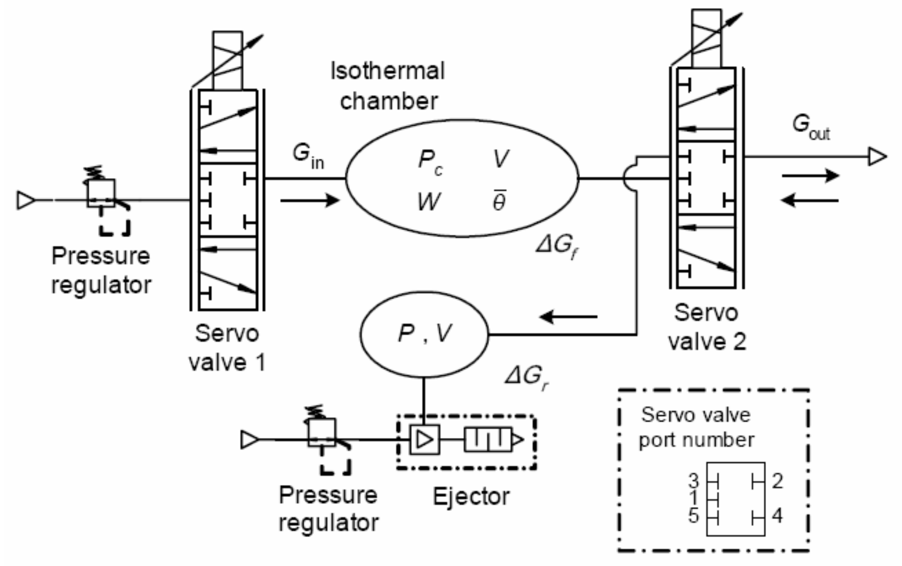

Fig. 1. Schematic diagram of the oscillatory gas flow generator

$$\frac{dP_c}{dt} = \left(G_{in} - G_{out}\right)R\overline{\theta} + WR\frac{d\overline{\theta}}{dt} \quad (2)$$

Here, the mass flow Gin is charged through servo valve1 installed in the upstream of the isothermal chamber. The controlled mass flow Gout, which is the generated flow of the forward direction, is discharged through servo valve2 installed in the downstream of the isothermal chamber. The generated flow Gout is given by the following equation by transforming Eq.(2):

$$G_{out} = G_{in} - \frac{V}{R\overline{\theta}}\frac{dP_c}{dt} + \frac{W}{\overline{\theta}}\frac{d\overline{\theta}}{dt} \quad (3)$$

If the state of the air in the chamber during charge or discharge remains isothermal, the forward part of the generated mass flow rate can be obtained from Eq.(3) as

$$G_{out} = G_{in} - \frac{V}{R\overline{\theta}}\frac{dP_c}{dt} = G_{in} - \Delta G_f \quad (4)$$

Since the condition remains isothermal, the average temperature in the chamber $\overline{\theta}$ is equal to the room temperature θ_a. Eq.(4) indicates that if the volume of the chamber V and the room temperature θa are known, then the generated mass flow rate can be controlled by the pressure difference in the isothermal chamber and the inlet mass flow rate. The flow rate through the servo valve is given in the following formula for the choked condition:

$$G_{in} = KS_e(u)P_s\sqrt{\frac{273}{\theta_a}} \qquad \left(\frac{P_c}{P_s} < b\right) \quad (5)$$

where b is the critical pressure ratio. The critical pressure ratio is defined in ISO 6358 (1989). The reverse flow is generated as follows. The flow is vacuumed to the chamber attached the ejector by switching and controlling the port of servo valve2. The flow rate through servo valve2 is given in the following Eq.(6) for the choked condition. Therefore, a maximum mass flow rate of the reverse flows depends on the size of the effective area of the servo valve and the atmospheric pressure. As a result, the inlet mass flow rate and the pressure change in the isothermal chamber are controlled by servo valve1, as shown in Fig.1, and the pressure change in the isothermal chamber and the generated reverse flow are controlled by servo valve2. In addition, when we realize a change of the flow direction and the pressure control in the chamber, a static characteristic of a servo valve is very important. Therefore, we measured a lot of data like Fig.2 finely, and we acquired the curve that was similar from the measured results smoothly and used.

$$G_{out} = \Delta G_r = KS_e(u)P_a\sqrt{\frac{273}{\theta_a}} \qquad \left(\frac{P_m}{P_a} < b\right) \quad (6)$$

Apparatus

A schematic diagram and a photograph of the developed generator are shown in Figs.3 and 4, respectively. The apparatus consists of an isothermal chamber as shown in Fig.5, two spool type servo valves as shown in Fig.6, four pressure sensors, a laminar flow meter, an ejector, a 16-bit AD converter, a16-bit DA converter and a personal computer. The servo valves (MPYE-M5-SA, FESTO Co.,Ltd.) that have a dynamic response of approximately 100[Hz] are used. Servo valve 1 controls the charged mass flow rate to the isothermal chamber, and servo valve2 controls the generated oscillatory mass flow rate with the both directions. The ejector (CV-15HS, MYOTOKU Ltd.) is used for making the vacuum pressure. And the semiconductor type pressure sensors (PM64S-500K, JTEKT Co.,Ltd.) having a resolution of 50[Pa] are used for absolute pressure measurement. The pressure sensor (AP-C30, KEYENCE CORPORATION) is used for vacuum pressure measurement and the pressure sensor (KL-80, NAGANOKEIKI Co.,Ltd) is used for atmospheric pressure measurement. A laminar flow meter as shown in the work by T.Funaki et al. (2004) with high speed response was arranged on the downstream side of the mass flow generator, as shown in Fig.4, and was used to verify the generated oscillatory mass flow. An AD/DA multi function board PCI-3176 and a DA board PCI-3336 made by Interface Co.,Ltd. Are used to obtain the supply pressure, the pressure in the isothermal chamber, the vacuum pressure, the atmospheric pressure ,the measured flow rate using a laminar flow meter and the control signals to the servo valves. An isothermal chamber whose volume 1.0×10^{-4}[m^3] is used. A copper wire with the diameter 5.0×10^{-5}[m] was filled 420[kg/m^3] to the isothermal chamber.

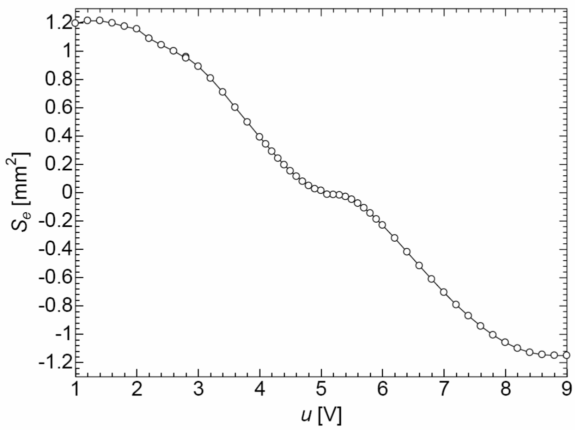

Fig. 2. Effective area of the servo valve to the control voltage

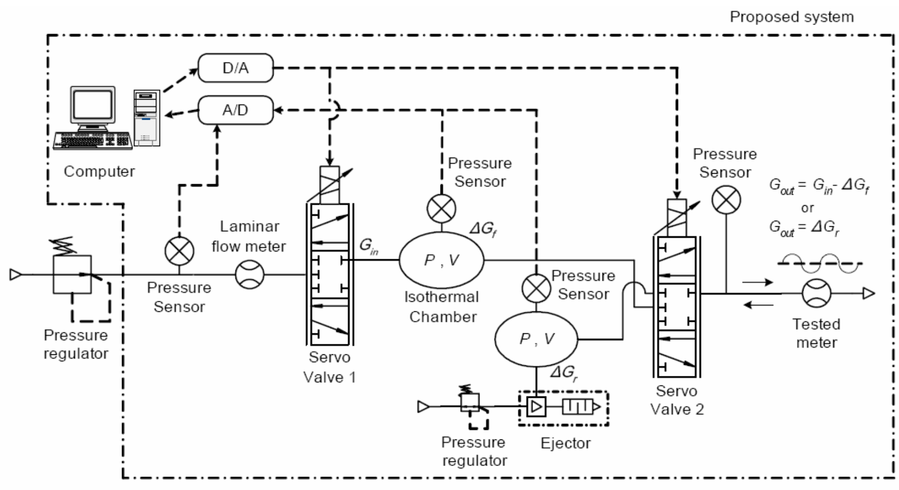

Fig. 3. Apparatus of oscillatory flow generator

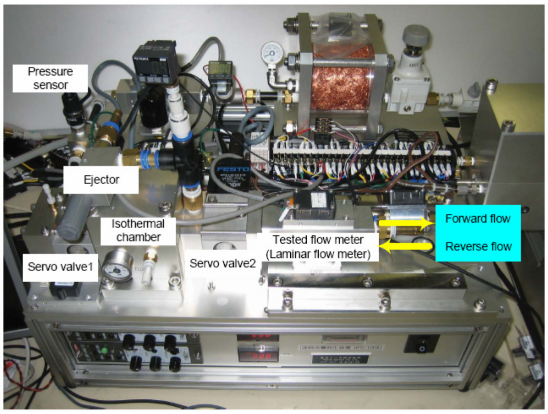

Fig. 4. Photograph of oscillatory flow generator

CONTROL METHOD

The oscillatory gas flow generator was adopted the switching and controlling the control port of servo valve2 in the case of forward and reverse flows. Table.1. shows four cases of the control method. Case I and II are when the target average mass flow *Gave* = 0, that is, the forward flow and the reverse flow are symmetry. Case III and IV are the target average mass flow *Gave* > 0, that is, the time average flow becomes forward flow.

Forward flows

The supply pressure was set at 600 [kPa abs], and the pressure in the isothermal chamber is controlled to remain lower than 210 [kPa abs], that is, the pressure ratio keeps lower than 0.35. Therefore, the choked condition is realized at servo valve1 because the critical pressure ratio of this valve was determined in advance to be 0.35. The second term of Eq.(4) on the left side ΔG_f is controlled by servo valve2. If Case I and III is given, the inlet mass flow rate to the isothermal chamber which is controlled by servo valve1 is calculated by the average value of the forward part of the generated flow. Fig.5 shows the block diagram of the oscillatory gas flow generator. Since the displacement of the servo valve can be measured as a voltage, the relationship between the displacement of the spool and the effective area of the servo valve *Se* is measured in advance using a dry type gas meter. The pressure at *t* seconds in the chamber can be calculated from Eq.(4). Therefore, the flow gain of servo valve2 K_G can be estimated. K_G is a time varying value because the pressure in the isothermal chamber changes while generating the unsteady mass flow. The control signal to servo valve2 is estimated as $G/(K_G S_e)$. This value is given as a feed forward input to servo valve2. A PI controller is used to control the differentiated pressure, and an I controller is adopted for pressure control in the isothermal chamber. As a result, when the generator was generated the oscillatory flow in the case of the forward direction, the input voltage to servo valve2 can be written as

$$u = K_{dp}\left(1+\frac{1}{T_{dp}s}\right)\left\{\left(\dot{P}_c\right)_{ref}-\dot{P}_c\right\}+\frac{1}{T_p s}\left\{\left(P_c\right)_{ref}-P_c\right\}+\frac{G}{K_G S_e} \qquad (7)$$

The pressure in the isothermal chamber during charge and discharge was calculated by the following non-perfect (Lagged) differential equation:

$$\dot{P} = \frac{f_d s}{f_d s+1}P \qquad (8)$$

where f_d was determined according to the frequency of the generated flow rate. The gain of the controller was determined experimentally. When the target flow $G_{ave} > 0$ is given, the flow rate G_{ref} (=G_{out}), which is the reference input, is transformed into the differentiated pressure from Eq.(4) as

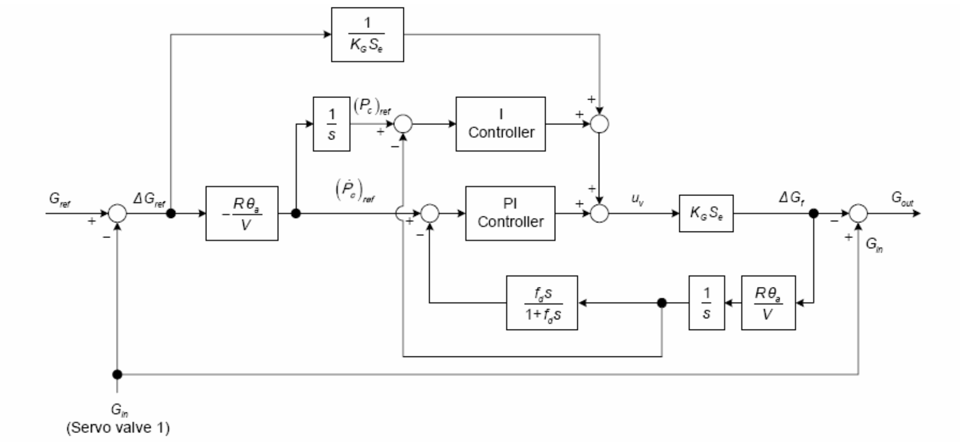

Fig. 5. Block diagram of oscillatory flow generator

Table 1. Patterns of flow rate control

Case No.	G_{ave} [kg/s]	Flow Direction	Servo valve1	Servo valve2
I	= 0	Forward	Closed	1 → 2
II	= 0	Reverse	1 → 2	2 → 3
III	> 0	Forward	1 → 2	1 → 2
IV	> 0	Reverse	1 → 2	2 → 3

$$\left(\dot{P}_c\right)_{ref} = -\frac{R\theta_a}{V}\left(G_{ref} - G_{in}\right) \tag{9}$$

The input signal to servo valve1 is closed position and the input voltage to servo valve2 can be obtained from Eq.(7) while generating the forward flows.

Reverse flows

The vacuum pressure is generated by an ejector and controlled to remain lower than 20[kPa abs]. Therefore, the pressure ratio between the pressure in the chamber and the atmospheric pressure keeps lower than 0.35. The flow rate characteristic of servo valve2 is measured in advance using a dry type gas meter. The control signal to servo valve2 is given by using its characteristics obtained from Eq.(6). As a result, if the target flow $G_{ave} > 0$ is given, the average value of the generated flow is given by the inlet mass flow rate to the isothermal chamber which is controlled by servo valve1. And, if the target flow $G_{ave} = 0$ is given, the control signal to servo valve1 is given by Eq.(7) and Eq.(10) while generating the reverse flow.

PRECISE AND QUICK RESPONSE PRESSURE REGULATOR

In order to realize a gas pulsation duplicating system which can test the dynamic characteristics of flow meters under pressurized conditions, pressure regulators are essential components. In former researches, in order to test the dynamic characteristics of flow meters under pressurized conditions, a buffer tank and a commercial available pressure regulator is set at the downstream of the tested flow meter. However, the responses of most of these commercial regulators are relatively slow. However, even this is largely inadequate. For regulators which are combined with oscillatory flow generators, the need for quick response and accuracy must be addressed. 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.

STRACTURE OF THE PROPOSED PRESSURE REGULATOR

A schematic and photograph of the proposed pressure regulator are shown in Figs. 6 and 7, respectively. It is composed of an SP valve (FESTO MPYE-5-M5-B), a QFS, an isothermal chamber, a PD sensor 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 used herein has a volume V of 1.0×10^{-3} [m^3]. The ‘PD sensor’ measures the pneumatic pressure differential with high precision and a quick response. 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. 8, 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 research is about 200 [Pa/s], and the break point frequency of the sensor is about 190[Hz].

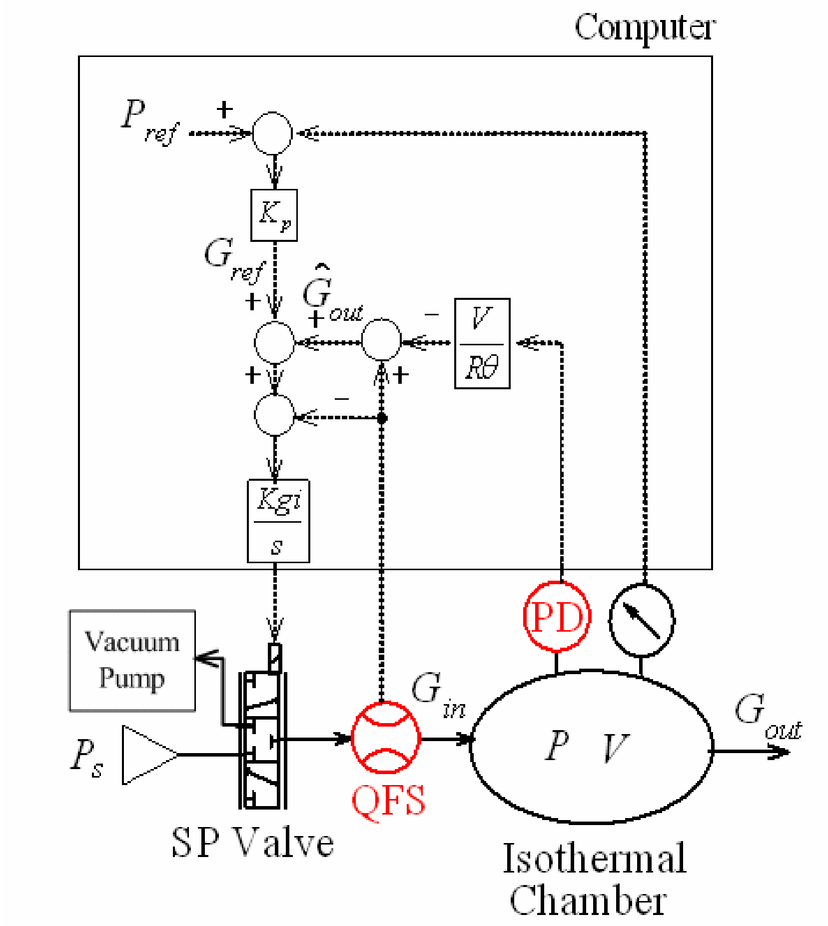

Fig. 6. Proposed pressure regulator schematic

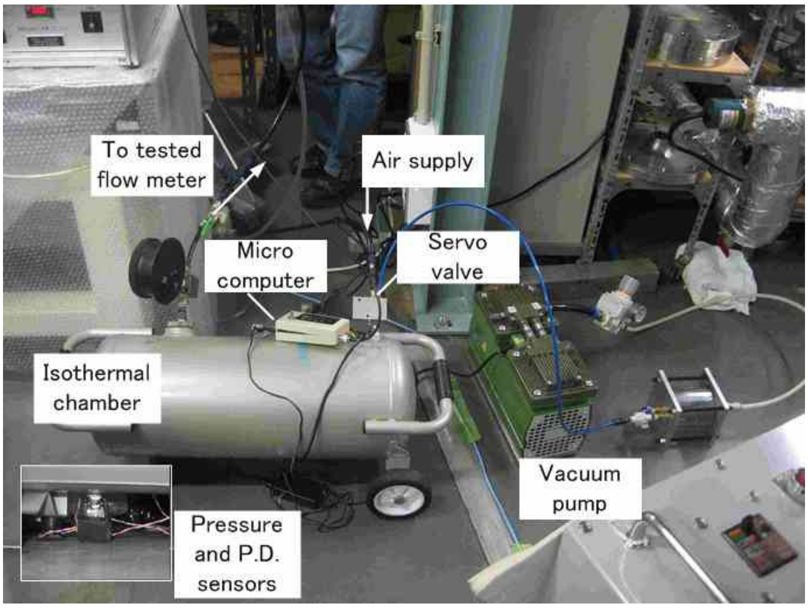

Fig. 7. Photograph of the fabricated pressure regulator

CONTROLLER DESIGN

The purpose of the pressure regulator developed herein is to maintain the pressure in the isothermal chamber at a set value. The component to be supplied, i.e. the pneumatic vibration isolator, is connected downstream of the isothermal chamber. The important point is that, irrespective of upstream or downstream disturbances, the pressure in the isothermal chamber should be maintained.

A block diagram of the proposed pressure regulator is shown in Fig. 8. The SP valve characteristics are approximated to the linear constant K_v. There are one main loop and two minor loops. The main loop is a pressure feed back loop. One of the minor loops, "Minor Loop 1", is a flow rate control loop which compensates for the nonlinear characteristics of the SP valve and can also reduce the affects of supply pressure variation. The other minor loop, "Minor Loop 2", estimates and compensates the output flow rate G_{out} (an upstream disturbance for pressure control). Noting the isothermal conditions, total differentiation of the state equation for the air leads to:

$$G_{in} - G_{out} = \frac{V}{R\theta}\frac{dP}{dt} \tag{10}$$

Therefore, by measuring G_{in} using the QFS and measuring dP/dt using the PD sensor, $\hat{G}_{out}$, which is the estimated value of G_{out} can be calculated:

$$\hat{G}_{out} = G_{in} - \frac{V}{R\theta}\frac{dP}{dt} \tag{11}$$

By positively feeding $\hat{G}_{out}$ back to the flow rate controller, when a disturbance occurs downstream of the isothermal chamber, the pressure P recovers immediately. G_{out} is usually measured using a flow sensor such as a QFS. However, this presents a restriction to flow leading to a pressure loss of up to several hundred Pascals.

With reference to Fig. 8, assuming that the time constants of the minor loops are much shorter than that of the main loop, the transfer function of the main loop can be expressed:

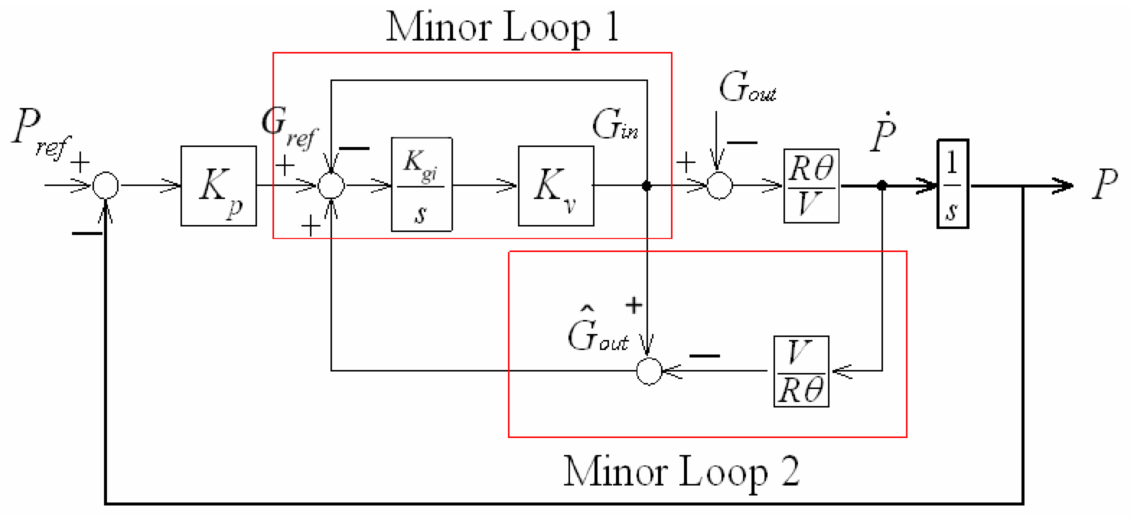

Fig. 8. Block diagram of the proposed pressure regulator

$$\frac{P}{P_{ref}} = \frac{1}{1+T_p s} = \frac{1}{1+\frac{V}{K_p R\theta}s} \tag{12}$$

In order to make T_p=0.75 [s], the proportional controller gain K_p is set at 0.4×10^{-7} [kg/(s・Pa)]. Suppose the flow rate loop (Minor Loop 1) has a reference value of G_{ref} and an integral controller gain of K_{gi}, the transfer function can be written:

$$\frac{G_{in}}{G_{ref}} = \frac{1}{1+T_G s} = \frac{1}{1+\frac{1}{K_v K_{gi}}s} \tag{13}$$

K_{gi} is set to 49.5×10^{5} [Pa/kg] which leads to a value of T_G of about 0.0075 [s]. Consequently, T_p:T_G=15:1. The sampling time of the controller is 1.0[ms].

TESTED FLOW METER

The type of flow meter used in this research is laminar flow type, which is composed of a laminar flow element and a differential pressure gauge. The photograph and specifications of the flow meter, named QFS, are shown in Fig. 9 and Table 2.

EXPERIMENT

Experiments were carried out with the apparatus arrangement shown in Fig.10. In Fig.10, the oscillatory flow generator is set upstream of the tested flow meter, i.e., QFS. And the quick and precision pressure regulator is set downstream of QFS, so as to control the bias pressure of line. In experiment, the target values of flow rate were set as (14).

$$G_{ref} = 5.0\times\sin(2\pi f t) \qquad \text{[L/min ANR]} \tag{14}$$

Where, f= 1,3,5 [Hz].

The target values of bias pressure, P_{ref}, were set 2.3[kPa gauge](which is almost same the value of

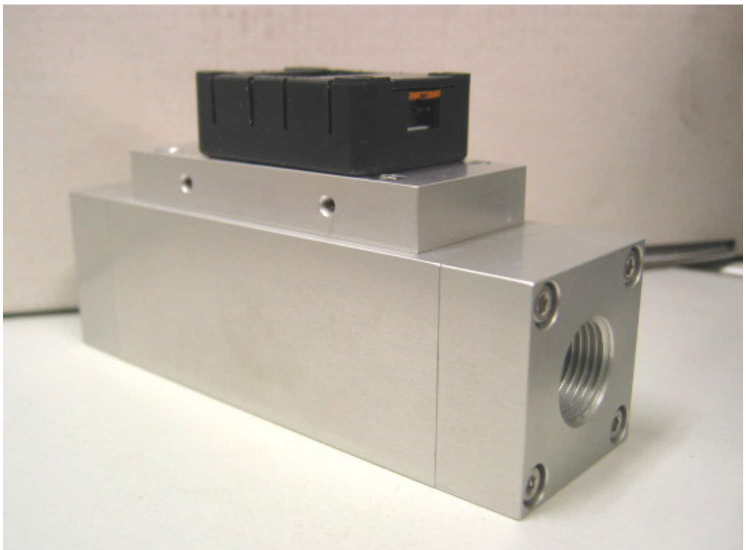

Fig. 9. Photograph of Quick Flow Sensor (QFS)

Table 2 Specifications of QFS

L mm	50
D mm	10
Diameter of Capillary mm	0.5(Outer) 0.3(Inner)
Maximum Measurable Flow Rate m^3/s	9.33×10^{-5}
Minimum Measurable Flow Rate m^3/s	9.33×10^{-8}
Number of Capillary	about 320
Differential Pressure Sensor	Nagano-keiki KL-17 ±1kPa

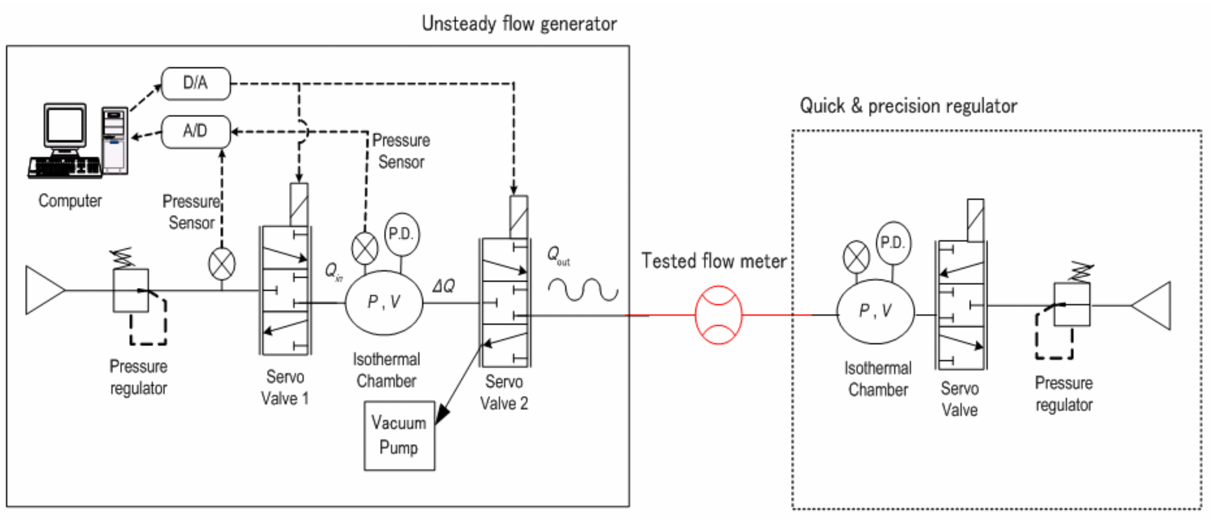

Fig. 10. Proposed test bench schematic

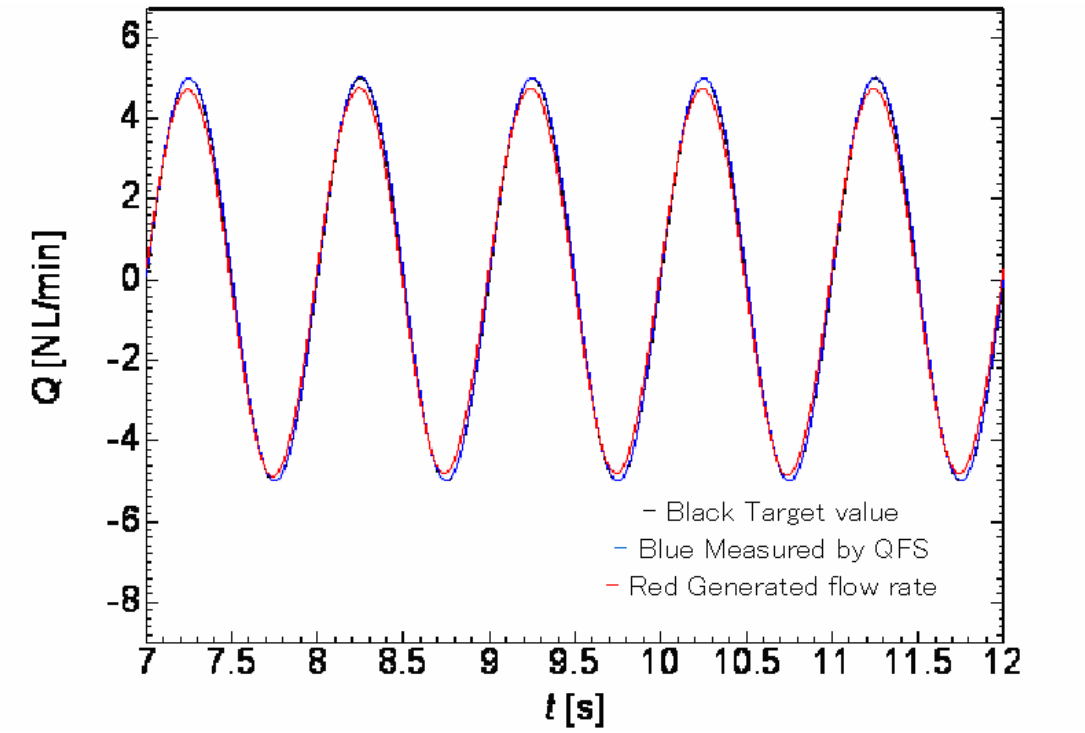

Fig. 11. Experimental results

commercial gas pipe line in Tokyo) and 5.0[kPa gauge].

The experimental results when f=5.0[Hz] and $P_{ref} = 5.0[\mathrm{kPa}]$ are shown in Fig.11. In Fig.11, the sinusoidal oscillatory flow is generated finely in spite of pressurized bias line condition. The target, generated and measured flow rates agrees well. The uncertainty is less than 10 percent. These results, of course guarantees, the dynamic characteristics of the tested QFS.

CONCLUSIONS

In this research, in order to realize a pulsation duplication system, we developed a test bench using an oscillatory gas flow generator and a quick and precision pressure regulator, both invented in our former researches. The test bench can test the dynamic characteristics of flow meters under pressurized conditions. As an example, a laminar flow type flow sensor, named QFS, was tested. The experimental results, up to f=5.0[Hz] and $P_{ref} = 5.0[\mathrm{kPa}]$ show in Fig.10. In Fig.10, guarantee the performance of the test bench. And also, the dynamic characteristics of the tested QFS were shown.

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