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DEVELOPMENT OF UNSTEADY GAS FLOW GENERATOR FOR EVALUATING THE DYNAMIC CHARACTERISTIC OF RESPIRATORY GASEOUS FLOW METER

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ABSTRACT

Respiratory gaseous flow measurement is one of an unsteady gas flow measurement and becoming very important. It has a wide field of application, for example, a measurement of lung function, an evaluation of respiratory gas exchange, a grasp of medical condition and so on. Especially, the evaluation of the absolute quantity and the analysis of the breathing waveform pattern are very important in the respiratory gaseous flow measurement. However, the dynamic characteristics of the respiratory gaseous flow meter has not been quantitatively measured and evaluated in the actual unsteady flows.

There is substantial literature dealing with the measurement of unsteady gas flow. Most of these studies generated unsteady mass flows by using piston cylinders. Clearly, in these studies, substantial efforts must have been required in order to minimize the sensitivity dependence of density fluctuation on pressure and temperature variations. On the other hand, the dynamic characteristic evaluation of the gaseous flow meter which reproduced the sinusoidal waveform with only a single frequency component in the measurement frequency band was typically enough. However, the respiratory airflow waveform with the various frequency components and the shapes is complicated. Moreover, we already know that the respiratory waveform pattern changes by a state of health and activities.

To solve these problems, this paper deals with the development of unsteady gas flow generator for the various breathing waveform reproduction. At first, we carry out the survey on the respiratory gaseous flow. Based on the research background and the above mentioned survey, we develop and introduce the unsteady gas flow generator which can generate the various respiratory flows. And we show the effectiveness of the developed unsteady gas flow generator. Moreover, we conduct the performance evaluation of the developed unsteady gas flow generator and the uncertainty analysis.

INTRODUCTION

In medical field, a respiratory gaseous flow measurement is becoming important increasingly. Respiration is the exchange of oxygen and carbon dioxide between an organism and its environment.[1] Ventilation can be defined as the movement of air between the atmosphere and the lungs.[2] Gas flow into and out of the respiratory system is influenced by the pressure gradient between the airway opening and the alveoli and the impedance offered by the lungs and the chest wall. And the mechanics of breathing can be assessed by measuring the air volume exchanged during ventilation, the gas flow into and out of the lungs, and the pressure that must be generated to achieve a given volume or flow during breathing. Therefore, the respiratory gas flow is one of the unsteady flows with bidirectional airflows. Here, the usefulness of respiratory gas flow measurements ultimately depends on the accuracy and the precision of the instrument used.

The respiratory gaseous flow measurement has a wide field of application. In general, the various kinds of gaseous flow meter have been widely used [1,3], for example, thermal flow meter, turbine flow meter, thermal flow meters manufactured by the MEMS or NEMS technique, several different types of pneumotachographs including the laminar flow meter and so on. However, the dynamic characteristics of the respiratory gaseous flow meter has not been quantitatively measured and evaluated in the actual unsteady flows.

Measurement of the unsteady flow rate of compressible fluids in industry is becoming more important with respect to energy savings and environmental protection in the work by R.W.Miller (1996).[4] There is substantial literature dealing with the measurement of unsteady gas flow. R.C.Mottram et al. (1992)[5] investigated the influence of pulsating flows on orifice plate flow meters. E.Hakansson et al. (1994)[6], J. Berrebi et al. (2004)[7] and H.J.Dane (1998)[8] studied the effects of pulsating flows on ultrasonic gas flow meters. C.R.Stone and S.D.Wright (1994)[9] investigated the dynamics of viscous flow meters both theoretically and experimentally. Most of these studies generated unsteady mass flows by using piston cylinders. Clearly, in these studies, substantial efforts must have been required in order to minimize the sensitivity dependent of density fluctuation on pressure and temperature variations. F.Durst et al. (2003 and 2007)[10,11] developed a mass flow rate controller using a valve and a laminar element that was designed to work up to unsteady oscillatory flow of 125Hz and showed experiment results of various wave form up to 25 [Hz]. Since the flow passed through a valve becomes a function of temperature, the accuracy could be improved if the temperature change is prevented. As a result, the unsteady flow measurement of gases is still a challenging research topic and the method to calibrate the dynamic characteristic of gaseous flow meters has not been defined yet. Therefore, we have developed a generator of oscillatory gas flows using an isothermal chamber to calibrate the gaseous flow meters by our groups (T.Funaki et al., 2006 and 2007)[12,13]. The experimental tests revealed that the generator can generate oscillatory flows with an uncertainty of 5%. Here, the dynamic characteristic evaluation of the gaseous flow meter which reproduced only a single frequency component was enough. However, the breathing waveform including the various frequency components and the shapes is complicated. Moreover, we already know that the waveform pattern changes by a state of health and activities or under stress.

To solve these problems, this paper deals with the development of unsteady gas flow generator for breathing waveform reproduction in order to achieve the dynamic calibration of the respiratory gaseous flow meters. At first, we carry out the investigation of the breathing waveform pattern. In addition, we actually measure the various respiratory airflows using the gaseous flow meter with high speed response. And we introduce the principle, the specification and the control method of the developed unsteady gas flow generator. Then, we evaluate the limitation of the developed unsteady gas flow generator and show the effectiveness of the developed generator which can generate the various breathing waveform. Moreover, we conduct the investigation of control method and the uncertainty analysis.

SURVEY ON RESPIRATORY FLOW

This chapter deals with the survey on respiratory flow from the various points of view.

Actual respiratory flow

The measurement method of the actual respiratory gaseous flow has not been confirmed yet. We already know that the maximum value of the respiratory flow is about 0.324 [g/s], the bandwidth of the frequency component is typically from 0.2 [Hz] to 2 [Hz].

On the other hand, we already know that the waveform of the respiratory gaseous flows indicate commonly rectangular waveform including constant, sinusoidal flow, ascending ramp flow, descending ramp flow, decaying exponential flow as shown in Fig.1.

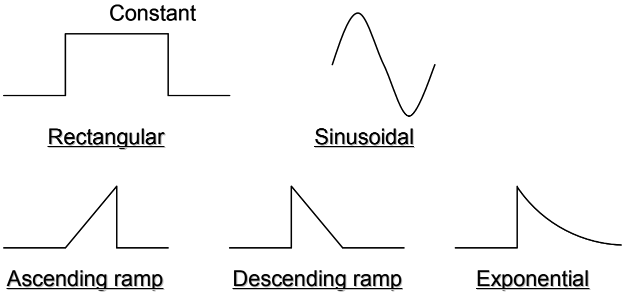

Fig.1 Typical waveform of respiratory flow

Ventilator

Many types of ventilators are available for adult and pediatric care in hospitals, for patient transport and so on. Especially it is important that the ventilator provides a breath or gas flow to a patient. Therefore, the main purpose of ventilation is to bring in fresh air for gas exchange into the lungs and allow the exhalation of air that contains carbon dioxide. As a result, the respiratory gas flow is one of the unsteady flows with bidirectional airflows. Here, the usefulness of respiratory gas flow measurements ultimately depends on the accuracy and the precision of the instrument used. Moreover, the ventilation is the basic concept of airflow. Air always flows from the high pressure point to the low pressure point. Therefore, the management and the control of the respiratory flows are very important.

Present various kinds of ventilators allow the clinician to choose among various inspiratory flow waveforms. Typical ways are “Volume controlled ventilation”, “Pressure controlled ventilation”, “Pressure support ventilation”. Inspiratory airflow waveforms can be categorized as constant or descending ramp flow. With pressure controlled ventilation, the inspiratory flow is determined by the resistance and compliance of the respiratory system. Moreover, with pressure support ventilation, the initial inspiratory flow and the frequency component of it are high. On the other hand, the expiratory flow is determined by alveolar driving pressure, airways resistance, the elapsed expiratory time, and the time constant of the respiratory system, that is, the lung system.

Respiratory gaseous flow meter

The respiratory gaseous flow measurement has a wide field of application, for example, a measurement of lung function, an evaluation of respiratory gas exchange, a grasp of medical condition and so on. In general, the various kinds of gaseous flow meter have been widely used. Recently, MEMS or NEMS technique have significantly improved our ability to evaluate patient respiratory function in the laboratory. As a result, the various kinds of thermal flow meters manufactured by the MEMS or NEMS technique have been developed. On the other hand, several different types of pneumotachographs including the laminar flow meter, the screen mesh type flow meter, a variable orifice flow meter, the general orifice plate, the variable area flow meter, an ultrasonic flow meter are used. However, the dynamic characteristics of the respiratory gaseous flow meter has not been quantitatively measured and evaluated in the actual unsteady flows.

UNSTEADY GAS FLOW GENERATOR

Principle

The unsteady gas flow is generated using an isothermal chamber, two spool type servo valves and an ejector as shown in Fig.2. Here, ΔG_f is the forward part of the amplitude of the oscillatory flow and ΔG_r is the reverse part of it 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:

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

Here, the mass flow G_{in} is charged through servo valve1 installed in the upstream of the isothermal chamber. The controlled mass flow G_{out}, 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 G_{out} is given by the following equation by transforming Eq.(2):

$$G_{out} = G_{in} - \frac{V}{R\bar{\theta}}\frac{dP_c}{dt} + \frac{W}{\bar{\theta}}\frac{d\bar{\theta}}{dt} \tag{3}$$

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

$$G_{out} = G_{in} - \frac{V}{R\bar{\theta}}\frac{dP_c}{dt} = G_{in} - \Delta G_f \tag{4}$$

Since the condition remains isothermal, the average temperature in the chamber $\bar{\theta}$ is equal to the room temperature θ_a. Eq.(4) indicates that if the volume of the chamber V and the room temperature θ_a 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:

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

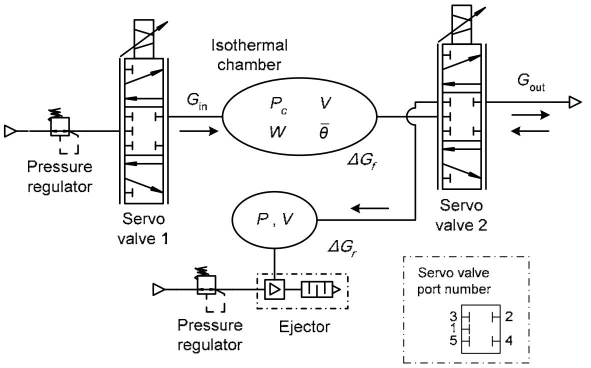

Fig.2 Schematic diagram while generating oscillatory gas flow

where b is the critical pressure ratio. The critical pressure ratio is defined in ISO 6358 (1989). The method of generation of the reverse flow using the unsteady gas flow generator is described in the following part. 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.2, and the pressure change in the isothermal chamber and the generated reverse flow are controlled by servo valve2. In addition, when the switch of the flow direction and the pressure control in the chamber have been realized, a static characteristic of a servo valve is very important. Therefore, we acquired the curve that was similar from the measured results smoothly and used.

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

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, two spool type servo valves, four pressure sensors, a laminar flow meter, an ejector, a 16-bit AD converter, a 16-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 2.0×10^{-4} [m^3] are used. A copper wire with the diameter 5.0×10^{-5} [m] was filled 420 [kg/m^3] to the isothermal chamber.

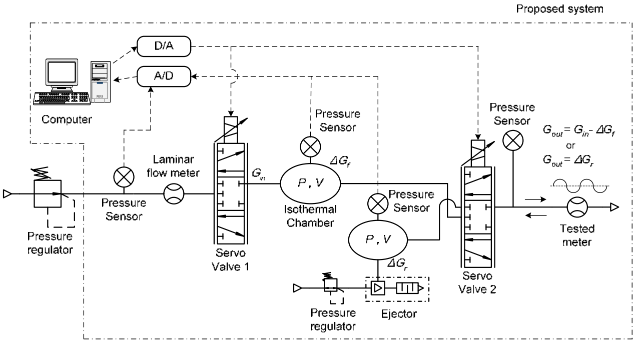

Fig.3 Apparatus of unsteady gas flow generator

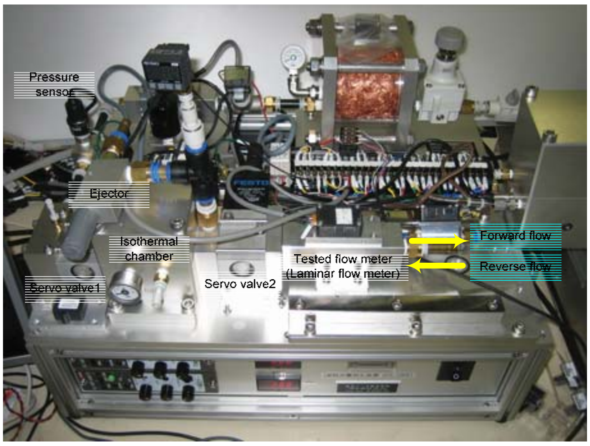

Fig.4 Photograph of unsteady gas flow generator

Table 1 Control method while generating the oscillatory flow

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

Control method

The unsteady gas flow generator was adopted the switching and controlling the control port of servo valve2 in the case of forward and reverse flows. Table1 shows four cases of the control method. Case I and II are when the target average mass flow $G_{ave} = 0$, that is, the forward flow and the reverse flow are symmetry. Case III and IV are the target average mass flow $G_{ave} > 0$, that is, the time average flow becomes forward flow. In this paper, the author deals with the reproduction of the respiratory flows using Case I and II.

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 unsteady 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 S_e 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 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

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

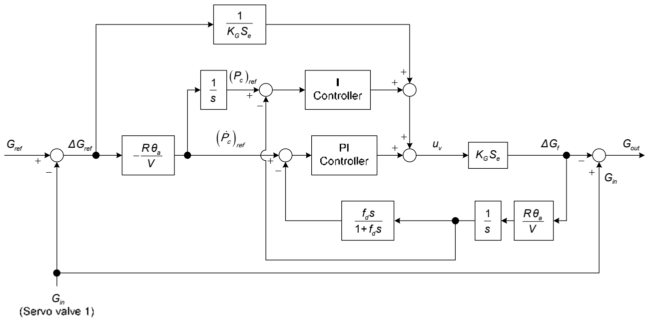

Fig.5 Block diagram of an unsteady gas flow generator while generating forward flows

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

$$\dot{P} = \frac{f_d s}{f_d s + 1} P \tag{8}$$

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

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

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 while generating the forward flow. The input signal to servo valve2 can be obtained from Eq.(7). When the target flow $G_{ave} = 0$ is given, the target flow rate G_{ref} is transformed into the differentiated pressure from Eq.(4) as

$$\left(\dot{P}_c\right)_{ref} = -\frac{R\theta_a}{V} G_{ref} \tag{10}$$

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 along with the generation of the forward flows. 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.

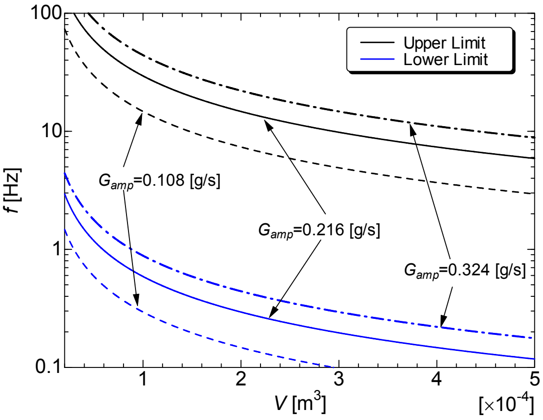

Fig.6 Limitation of unsteady gas flow generator

Limitation and Specification

The limitation of amplitude and frequency that can be generated with the unsteady gas flow generator is examined. However, the respiratory waveforms are complicated. Then, it is tested by the reproduction of the sinusoidal waveform with single frequency component. Since the variation of generated oscillatory mass flow rate is equivalent with the pressure change in the isothermal chamber, the pressure change in the chamber can be obtained from Eq.(4) as

$$\frac{dP}{dt} = \frac{R\theta}{V} G_{amp} \sin\left(2\pi f t\right) \tag{11}$$

When an expression (11) is integrated and arranged, the time variation of pressure in the chamber becomes the next expression.

$$P = P_{ave} - P_{amp}\cos\left(2\pi f t\right) = P_{ave} - \frac{R\theta G_{amp}}{2\pi f V}\cos\left(2\pi f t\right) \tag{12}$$

From this expression, the pressure change in the chamber can express the change in the sinusoidal waveform around a certain absolute pressure equilibrium point P_{ave}. And the pressure amplitude in the chamber becomes ($R\theta G_{amp}/2\pi f V$). The minimum value of this pressure amplitude ΔP_{min} is derived by the resolution of a pressure sensor measuring the pressure in the chamber. On the other hand, because a flow passing the servo valve1 must realize a choked condition, the upper limit value in the isothermal chamber is decided naturally. The pressure in the chamber changes only between the upper limit value and the atmospheric pressure. Therefore, the upper limit value of the pressure amplitude ΔP_{max} is determined. As a result, the range of the pressure amplitude in the chamber is derived in the next inequality.

$$\Delta P_{\min} \le \left|\frac{R\theta G_{amp}}{2\pi f V}\right| \le \Delta P_{\max} \tag{13}$$

Relation between the frequency and the chamber volume become the next inequality from Eq.(13) as a parameter by the amplitude of generated mass flow rate. Here, a constant number C is $R\theta/2\pi$.

$$\frac{C G_{amp}}{\Delta P_{\max}}\frac{1}{V} \le \left|f\right| \le \frac{C G_{amp}}{\Delta P_{\min}}\frac{1}{V} \tag{14}$$

From this Eq.(14), as for the relations of the frequency and the chamber volume, the following graphs as shown in Fig.6 are provided. In this graph, the amplitude of the generated mass flow rate shows a case of 0.216 [g/s] by a solid line and shows a case of 0.108 [g/s] in a dashed line respectively. And the dashed-dotted line indicates a case of 0.324 [g/s]. The black line shows the upper limit value. The blue line shows the minimum value. When the amplitude of generated flow rate is fixed, if a chamber volume becomes big, the frequency lowers. Therefore, it may be said that a small chamber is necessary for generation of the oscillatory flow that the frequency is high. In addition, this graph is derived with Eq.(14), if we decide the amplitude of mass flow rate that we want to generate. And we may choose the frequency and the chamber volume between two curves. As an example satisfying this condition, Fig.7

shows the experimental results that the oscillatory mass flow rate is given as $0.216 \sin(2\pi f t)$ [g/s] at a frequency of 20 [Hz]. The proposed generator with isothermal chamber whose volume 2.0×10^{-4} [m^3] is thus proven to be capable of generating oscillatory flows.

EXPRIMENTAL RESULTS AND DISCUSSIONS

In this chapter, a few experiments were performed. At first, the author carried out the reproduction of typical waveform of the respiratory flows using the developed oscillatory gas flow generator. The experimental results of the sinusoidal waveform reproduction are shown in Fig.7. Here, the target mass flow rate is $0.216 \sin(2\pi f t)$ [g/s] at the frequency of 20 [Hz]. In this figure, the dashed line shows the target value. The solid line indicates the generated mass flow rate calculated from Eq.(4) and the blue solid line shows the measured flow rate using the laminar flow meter with high responsibility. From this figure, the generated mass flow rate and the measured mass flow rate agree well with the target mass flow rate. Therefore, it can be confirmed that the developed generator has been achieved the generation of the sinusoidal waveform.

Next, the generation of the rectangular wave form is examined. The experimental results are shown in Fig.8. The frequency condition is 1 [Hz]. The maximum mass flow rate is 0.216 [g/s], the minimum value is -0.216 [g/s]. In this figure, the dashed line shows the target mass flow rate, the solid line indicates the generated mass flow rate using the generator. Here, the low-pass filter was used for the processing of the measured data. The cut-off frequency of the filter was set at 20 [Hz]. From this figure, the generated values of the generator agree well with the target mass flow rate. Especially, transient change while switching the flow direction has been achieved quickly and precisely. On the other hand, it can be observed the small overshoot at the switching point of the flow direction. It has been considered that the effect of the pressure controllability in the isothermal chamber or the flow controllability of the servo valve appeared.

Fig.9 shows the experimental results of the reproduction of the ascending ramp waveform. From this figure, the generated values of the generator agree well with the target mass flow rate. However, it can be seen the small overshoot at the switching point of the flow direction on an equality with the reproduction of the rectangular waveform. Moreover, Fig.10 shows the experimental results of the reproduction of the descending ramp waveform. The target mass flow rate and the generated value show good agreement. And it can be confirmed the small fluctuation of the generated value using the generator. Fig.11 shows the reproduction of the decaying exponential waveform at the frequency of 0.5 [Hz]. From this figure, the generated values of the generator agree very well with the target mass flow rate. And the measured value using the laminar flow meter and the generated value show good agreement. Therefore, it is confirmed that this generator has been achieved and shown the reproduction of the typical respiratory waveform.

Finally, the author conducted the reproduction of the actual respiratory waveform. At first, the author measured own respiratory waveform using the laminar flow meter with high responsibility as the target value of the generator. Then, the generator had been reproduced the actual respiratory waveform.

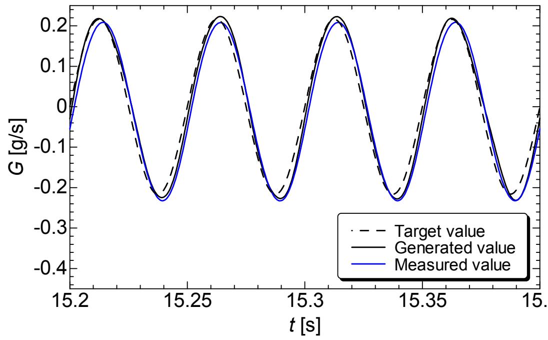

Fig.7 Sinusoidal waveform at the frequency of 20Hz

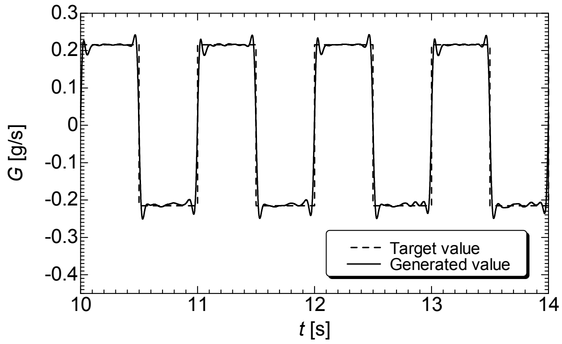

Fig.8 Rectangular waveform at the frequency of 1Hz

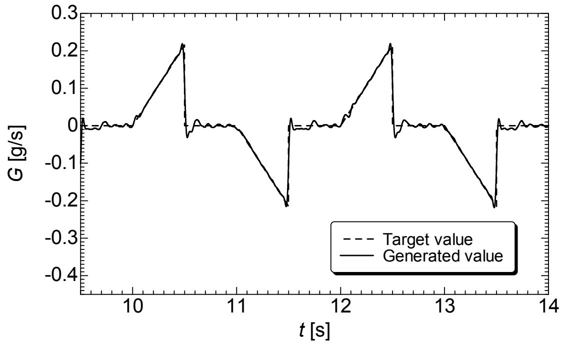

Fig.9 Ascending ramp waveform at the frequency of 0.5Hz

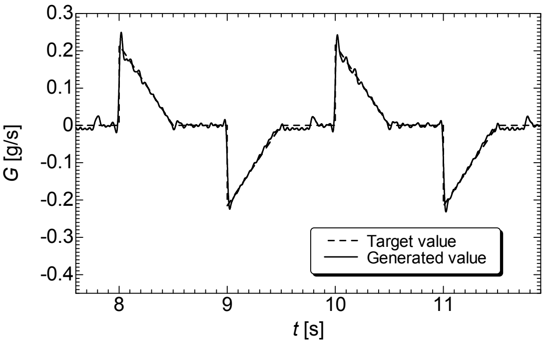

Fig.10 Descending ramp waveform at the frequency of 0.5Hz

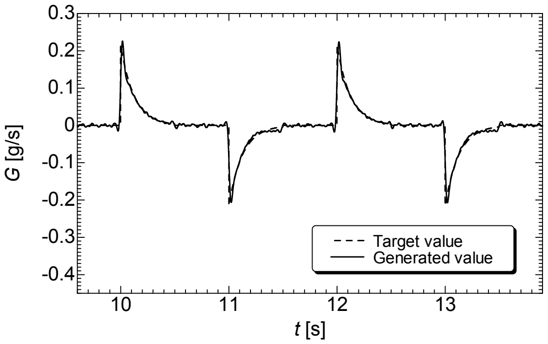

Fig.11 Decaying exponential waveform at the frequency of 0.5Hz

Fig.12 shows the experimental results. From the figure, the generated values agree well with the target mass flow rate.

On the other hand, Fig.13 shows the experimental results of the ventilator waveform reproduction with volume controlled ventilation. This waveform consists of the rectangular wave and the descending ramp wave. In this figure, the dashed line shows the target value, the solid line shows the generated value of this generator and the blue solid line shows the measured value using the laminar flow meter. As a result, three curves show good agreement. However, the small fluctuation of the generated waveform can be observed. It has been considered that the effect of the pressure or the differentiated pressure controllability in the isothermal chamber appeared. But it can be seen through these experiments that the developed generator has been achieved the reproduction of the various respiratory flows. Therefore, this generator is useful for the measurement of the dynamic characteristics of the respiratory gaseous flow meters.

DISCUSSIONS

Uncertainty analysis

The total uncertainty of the unsteady gas flow generator is given by the following formula from the propagation of uncertainty as shown in guide by ISO (1993 and 2002).

$$\frac{\delta G_f}{G_f}=\sqrt{\left\{\left(\frac{\delta P_s}{P_s}\right)^2+\left(\frac{\delta S_e}{S_e}\right)^2+0.25\left(\frac{\delta\theta}{\theta}\right)^2\right\}}+\sqrt{\left\{\left(\frac{\delta\theta}{\theta}\right)^2+\left(\frac{\delta V}{V}\right)^2+\left\{\frac{\delta(dP/dt)}{(dP/dt)}\right\}^2\right\}}+\sqrt{\left\{\left(\frac{\delta\theta}{\theta}\right)^2+\left\{\frac{\delta(d\theta/dt)}{(d\theta/dt)}\right\}^2\right\}} \quad (15)$$

$$\frac{\delta G_r}{G_r}=\sqrt{\left\{\left(\frac{\delta P_a}{P_a}\right)^2+\left(\frac{\delta S_e}{S_e}\right)^2+0.25\left(\frac{\delta\theta}{\theta}\right)^2\right\}} \quad (16)$$

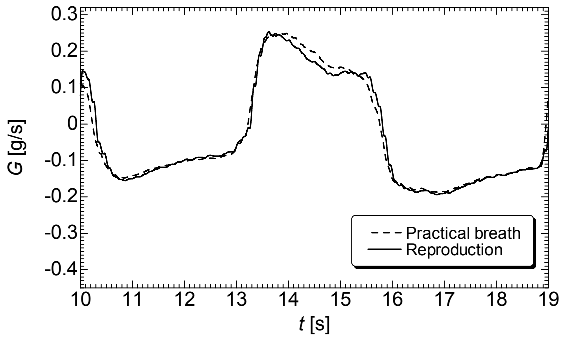

Fig.12 Reproduced example of actual respirator flow

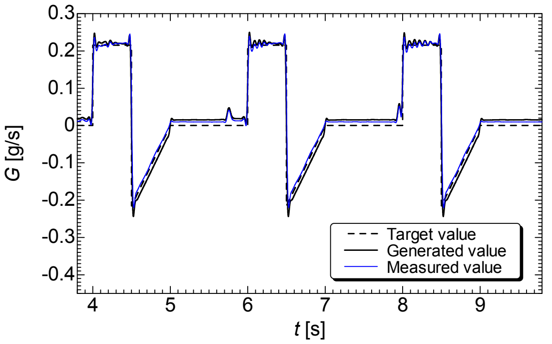

Fig.13 Reproduced example of volume controlled ventilation

Where the first term is the uncertainty of the inlet mass flow rate, the second term is the uncertainty of the pressure change of the isothermal chamber, and the third term is the uncertainty of the temperature change. The uncertainty of the chamber volume measurement is considered to be 0.5 [%]. The uncertainty of the effective area is considered to be 0.5 [%]. The uncertainty due to the pressure change speed is considered to be 1 [%]. The uncertainty of the temperature change is estimated as 3 [%] at maximum. The other factors affecting the uncertainty are as mentioned above. From Eq.(15), the generated mass flow rate with only forward direction has a maximum uncertainty of 4.8 [%]. On the other hand, the generated mass flow rate with only reverse direction has a maximum uncertainty of 1 [%] from Eq.(16). Therefore, the unsteady gas flow generator has sufficient accuracy for practical use and the evaluation of the dynamic characteristics of the respiratory gaseous flow meters.

CONCLUSION

In this paper, the author has proposed an unsteady gas flow generator which can useful for measuring and evaluating the dynamic characteristics of the respiratory gaseous flow meters. At first, we have explained the principle, the specification and the control method of the generator. And we have evaluated the limitation of the developed unsteady gas flow generator. Moreover, it has been confirmed that the generator can generate the typical waveforms of respiratory flows within an uncertainty of 4.8 [%]. Therefore, the effectiveness of the generator has been confirmed experimentally. Finally, this developed unsteady gas flow generator is useful of the measurement and the evaluation of the dynamic characteristics of respiratory gaseous flow meters.

NOMENCLATURE

a: Amplitude ratio of mass flow rate (G_{amp}/G_{ave}), b: Critical pressure ratio, C: Constant number, f: Frequency s^{-1}, f_d: Cut-off frequency s^{-1}, G: Mass flow rate kg s^{-1}, K: Coefficient of unit converter, K_G: Gain of flow rate kg (s m^2)$^{-1}$, K_p: Proportional gain of pressure V Pa^{-1}, K_{dp}: Proportional gain of differentiated pressure V (Pa s)$^{-1}$, k: Coefficient of flow rate converter m^3 kg^{-1}, P: Pressure Pa, P_a: Atmospheric pressure Pa, P: Differentiated value of pressure Pa s^{-1}, R: Gas constant J (kg K)$^{-1}$, s: Laplace variable, S_e: Effective area m^2, t: Time s, T_p: Integral action time of pressure s, u: Input voltage to the servo valve V, V: Volume of the chamber m^3, W: Mass of gas in the chamber kg, ΔG: Amplitude of mass flow rate kg s^{-1}, ΔP: Amplitude of pressure Pa, κ: Ratio of specific heats, θ: Temperature of gas K, θ_a: Room temperature K, $\overline{\theta}$: Average temperature K

The following subscripts were used in this paper.
amp: amplitude, *ave*: average, *c*: chamber, *e*: control volume, *f*: forward direction, *in*: inlet, *max*: maximum, *min*: minimum, *out*: outlet, *r*: reverse direction, *ref*: target, *s*: supply

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