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A New Control Method Utilizing Multiplex Air Vibration for Multi-DOF Pneumatic Mechatronics Systems

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***Abstract*— Pneumatic actuators have several advantages such as light weight, safety, low cost and high compliance. They have been used in many areas such as industrial robots, rehabilitation tools, haptic devices, and medical/welfare robots. Pneumatic actuators are generally used in multi-DOF pneumatic system and have complicated systems that include a compressor, air tubes, and pneumatic valves with electrical wires. This research proposes a new control method for a multiplex pneumatic transmission constructed with special resonant valves and driven independently with air vibration in air supply tube without electrical wires. The control method simplifies the driving system and is effective for pneumatic systems having many degrees of freedom. In this paper, the development of a prototype model of the resonant valve is described. In addition, two control methods, which are a superimposing method and a time-sharing method for multi-valve control, are proposed and evaluated. Independent control of four pneumatic cylinders is realized.**

I. INTRODUCTION

Pneumatic actuators are used in several areas, such as industrial robots, haptic devices, rehabilitation tools, and medical robots, because they have the advantages of light weight, low cost, safety, and high compliance. However, in a pneumatic system, a large compressor and many electrical wires from the control valve complicate the entire system. Generally pneumatic actuators are used in a system having multi degrees of freedom and the system becomes more complicated [1] [2]. Most of previous works are on downsizing of the pneumatic valves [3-6].

We have proposed a novel pneumatic control method as shown in Fig.1 and a pneumatic valve to solve the problem [7] [8]. This system which is called multiplex pneumatic control system is constructed with an oscillator, a resonant valve, and air tube. The oscillator causes air vibrations in air supply tube. The air tube is connected to resonant valves serially, and the resonant valves are selectively controlled by air vibration from the oscillator.

As shown in the Fig.1, to make the actuator 1 working the oscillator should be driven to generate air vibration at the frequency 1. The frequency 1 is a resonant frequency of the resonant valve connected to the actuator 1. Each resonant valve has a different resonant frequency, respectively. In the same way to drive the actuator 2 the air vibration at the frequency 2 should be in the air tube. To drive multi pneumatic actuators at the same time the superimposing vibration of two frequencies should be generated at frequency 3 as shown in Fig.1. In this proposed system the independent control of the multi DOF pneumatic system is realized through only one air tube line without electrical wires from the valve.

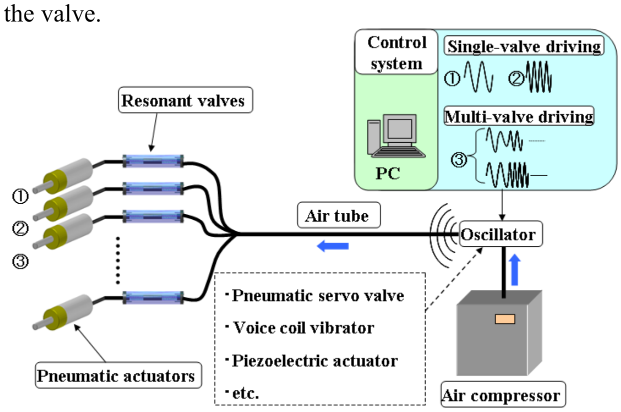

Fig.1 Proposed novel pneumatic control system which is called multiplex pneumatic transmission

As a similar research, Kitagawa et al. developed a pneumatic pilot valve driven by sound vibration using a speaker [9]. Two pneumatic pilot valves were developed and they achieved independent driving of the two valves. This system was applied to wearable devices in the caretaking and medical assistance areas.

Ikuta et al. developed a band pass valve driven by hydraulic pressure for a system with multiple degrees of freedom [10]. Several band pass valves can be individually controlled by different ranges of pressure. They applied these valves to a safe active catheter having two degrees of freedom.

The authors of this paper previously have proposed a working principle of multi-pneumatic actuator drive with superimposed air vibration, developed a prototype valve, and experimentally confirmed independent driving of pneumatic pressure [11-13].

In this paper, we realize independent control of multi DOF pneumatic system. First the principle of the resonant valve

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and new control method of time sharing for multi DOF system are described. Secondly, the design of the new prototype valve used in the experiment is described and the experimental results of the superimposing method used in the previous research and the new method based on time-sharing are compared. Finally experiments of independent control of four resonant valves are shown.

II. Working principles of the multiplex pneumatic control system

A. Working principle of the resonant valve

A working principle of the resonant valve is shown in Fig.2 [7] [8]. The resonant valve is configured with two mass-spring systems. The vibrators have channels as shown in Fig.2 and are pressurized each other by springs. The air-inlet port of this model is on the left side in this figure, and the air vibrations for valve control are included in this air flow. Two vibrators keep contacting each other when the frequency of air vibration is non-resonant frequency of this mass-spring system. In this case the air doesn't flow to the outlet port. However, when the frequency in the supply air is at the resonant frequency of this model the two vibrators repeats contact and non-contact actions. The air can flow to the outlet port through the channels in the two vibrators. In other words, this model is driven with specific air vibration transmitted in the air supply line, working as an on/off valve.

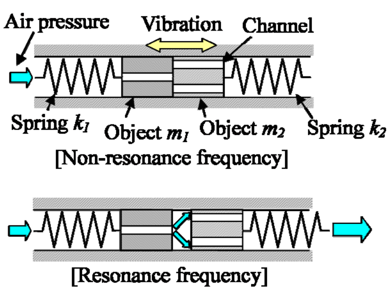


Fig.2 Principle model of proposed resonant valve

B. Superimposing and time-sharing methods

The resonant valve is controlled by the air vibration shown in Eq. (1). Air vibration to the resonant valve is produced by the high-speed valve as an oscillator, which is located near the compressor. In Eq. (1), V_p is the voltage parameter to the oscillator and f_n is the frequency of the driving valve. Single-valve control is realized by generating the resonant frequency.

$$V_p = amplitude \times \sin(2.0 \times \pi \times f_n \times t) + offset \tag{1}$$

In this report, we newly propose another control method for driving multiple resonant valves, which is named time-sharing method. In the superimposing method, the numbers of frequencies are combined as shown in Fig. 3 and

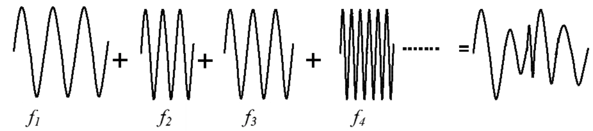


Fig.3 Multi-valve driving method 1; superimposing method

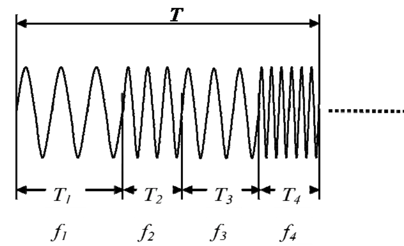


Fig.4 Multi-valve driving method 2; time-sharing method

Eq. (2), where m is the maximum number of resonant valves. Independent control of two pneumatic cylinders by the superimposing method was successful [13, 14].

$$V_p = \frac{1}{m} \times \sum_{n=1}^{m} \left(amplitude \times \sin(2.0 \times \pi \times f_n \times t) + offset \right) \tag{2}$$

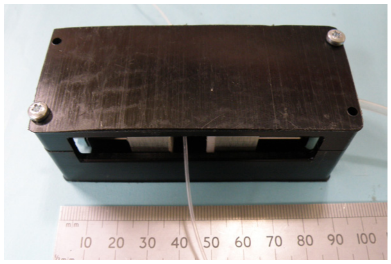
In the time-sharing method, different resonant frequencies are oscillated serially in a short time T, as shown in Fig. 4 and Eq. (3). Here, T_m is the parameter of the cycle of each resonant frequency. Each frequency is repeated as the cycle is connected serially from frequency (1) to frequency (m). Time T depends on the time constant and wavelength of each resonant frequency. It is effective because the cycle becomes shorter with high-frequency bands.

In this paper, we assume the number of driving prototype valves is four. The comparison of the two methods is described in an experiment of independent control.

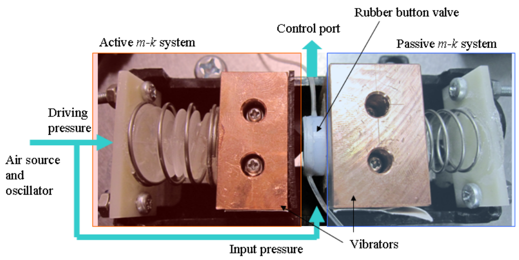
$$V_p = \begin{cases} frequency(1): (0 \le t \le T_1) \cdots amplitude \times \sin(2.0 \times \pi \times f_1 \times t) + offset \\ frequency(2): (T_1 \le t \le T_2) \cdots amplitude \times \sin(2.0 \times \pi \times f_2 \times t) + offset \\ frequency(3): (T_2 \le t \le T_3) \cdots amplitude \times \sin(2.0 \times \pi \times f_3 \times t) + offset \\ \vdots \\ frequency(m): (T_{m-1} \le t \le T_m) \cdots amplitude \times \sin(2.0 \times \pi \times f_m \times t) + offset \end{cases} \tag{3}$$

III. Design and fabrication of the prototype valve

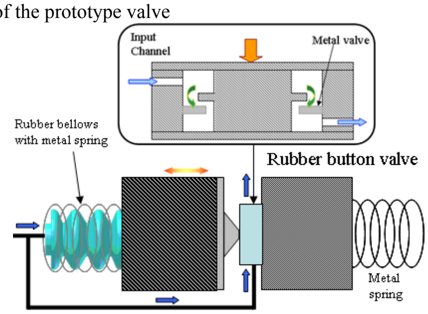
The appearance and the structure of the prototype valve which is developed and used in this paper are shown in Fig.5 [13]. This prototype valve is configured with two vibrators, a metal spring, a rubber bellows-metal combined spring, a rubber button valve, and a linear guide. The rubber bellows with metal spring transmit air vibration to the force for vibrators. The driving air line is connected to the rubber bellows and also to the input of the rubber button valve as shown in the figure. The rubber button valve is a key point of the development of the prototype valve. The rubber button valve works as an on/off valve by pushing its top.



(a) appearance of the prototype valve



(b) inside of the prototype valve



(c) principle and structure

Figs.5 Developed prototype valve of resonant valve

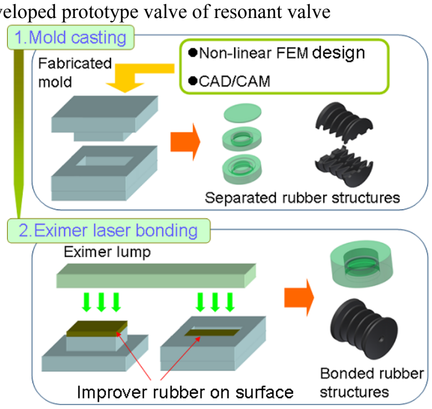


Fig.6 Manufacturing process of the rubber button valve [13]

The rubber button valve is manufactured by a simple method as shown in Fig.6. A mold for rubber fabrication is designed by non-linear finite element method (FEM) and fabricated by CAM. Two rubber parts are molded separately and bonded by excimer surface improvement processing. The operation of this valve as an on/off valve was confirmed in a step response experiment [13].

The resonant frequency of the prototype valve is designed by configuring the mass and spring constants in the mass-spring systems. The maximum frequency of the pneumatic valve generating air vibration as the oscillator is approximately 50 [Hz]. Therefore, the four different resonant frequencies of the four prototype valves have to be less than 50 [Hz]. The mass is configured by changing the material and volume. The materials are aluminum, stainless steel, copper, and polyacetal. The parameters of the four prototype valves are shown in Table 1. The theoretical resonant frequencies are shown in Table 1, which are calculated by Eq. (4).

TABLE 1 THE PARAMETERS OF FOUR PROTOTYPE VALVES

Valve	Material of vibrators	Active m-k system		Passive m-k system		Resonant frequency
		m_1(g)	k_1(N/mm)	m_2(g)	k_2(N/mm)	f_n(Hz)
A	Cupper	80.2	0.30	133.3	0.49	9.6
B	Stainless steel	33.2	0.30	86.7	0.49	12.9
C	Polyacetal	12.4	0.50	8.0	0.49	35.1
D	Alminum	23.9	0.30	25.2	0.50	20.3

$$f_n = \sqrt{\frac{(k_1 + k_2)}{(m_1 + m_2)}} \tag{4}$$

IV. EXPERIMENTS OF INDEPENDENT PNEUMATIC CONTROL

In this experiment, the purpose is confirmation of the independent control and comparison of performances with the superimposing and time-sharing methods. The experimental system for independent control is shown in Fig.7. Small leak valves are used as exhaust valves as shown in the figure. The output pressure is measured by the pressure sensor. A PC controls the oscillator and collects the data from the pressure sensors. The maximum amplitude pressure generated by the oscillator is about 0.1 [MPa].

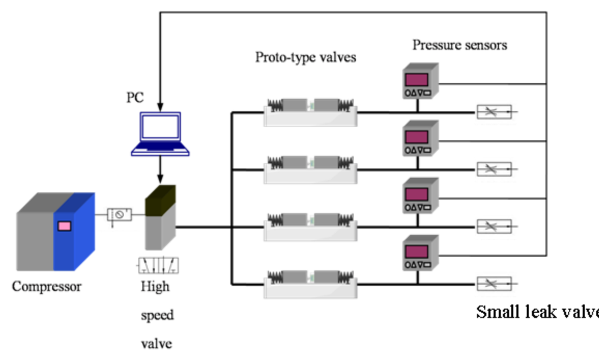


Fig.7 Experimental system for driving of the prototype valve

The basic properties of the valves such as the resonant frequencies, resonant bands, and the maximum output pressure are experimentally evaluated as shown in Fig.8 and Fig.9. Figure 8 shows the independent resonant property for 5 [Hz] to 40[Hz]. The output pressure can be controlled by changing the amplitude of the input signal of the oscillator as

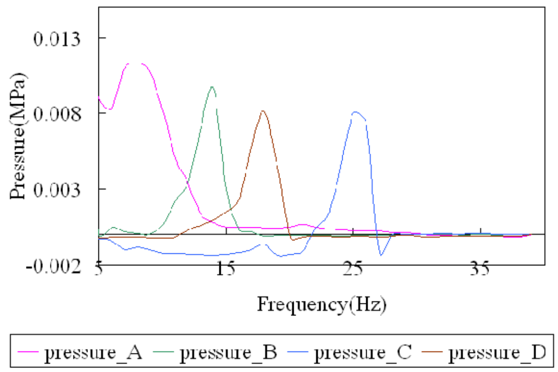


Fig.8 Experimental result of frequency response

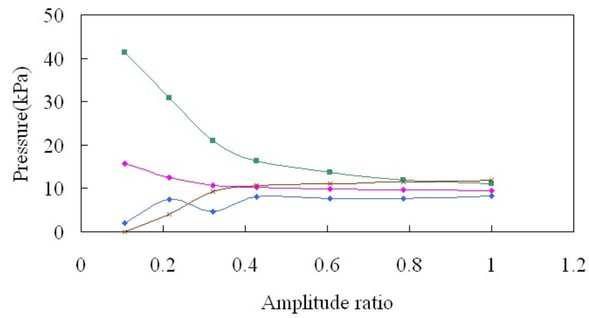


Fig.9 Experimental result of amplitude modulation

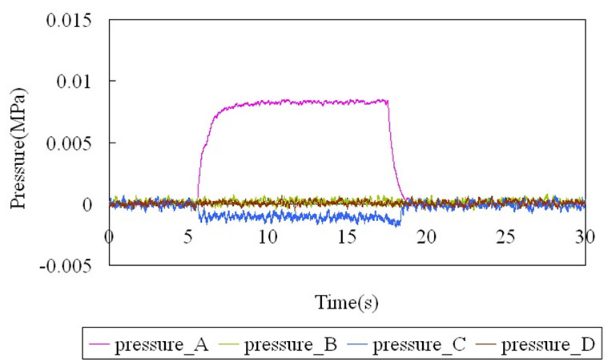
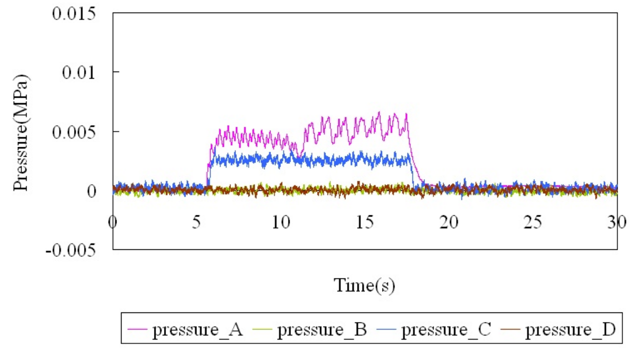


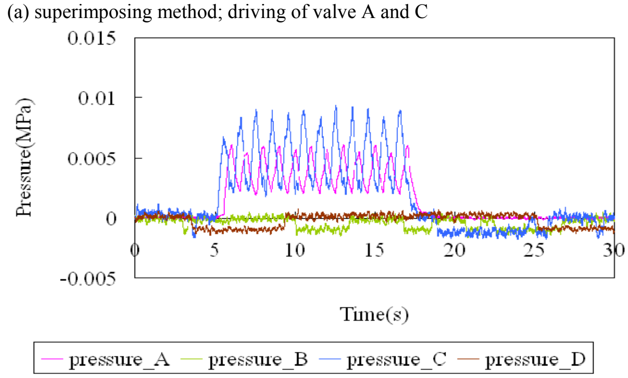
Fig.10 Experimental result of step response (valve A)

shown in Fig.9. An example of the experimental results for the step response of the valve A is shown in Fig.10. As shown in these results, independent driving of the prototype valves was confirmed.

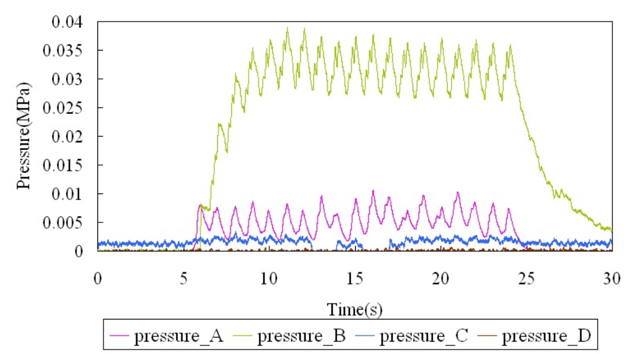
Figures 11, 12, and 13 show the experimental results for multi-valve driving: 2-valves driving in Fig.11, 3-valves driving in Fig.12, and all-valves driving in Fig.12. In each figure, Fig (a) shows the experimental results of superimposing method and Fig. (b) shows the results of time-sharing method. The superimposing control is successful in the experiment for 2-valves driving. However, this control method doesn't work well for 3-valve and all-valve drivings. In contrast, time-sharing method works well for any cases. The output pressures corresponding to each resonant frequency are confirmed in each figure. The output pressure value vibrates more by comparison with the single-valve driving. This vibration can be reduced by optimizing the cycle time of each frequency (T_1, T_2, T_3, and T_4 in Fig.4). The different waveforms result from the time constant of each valve.



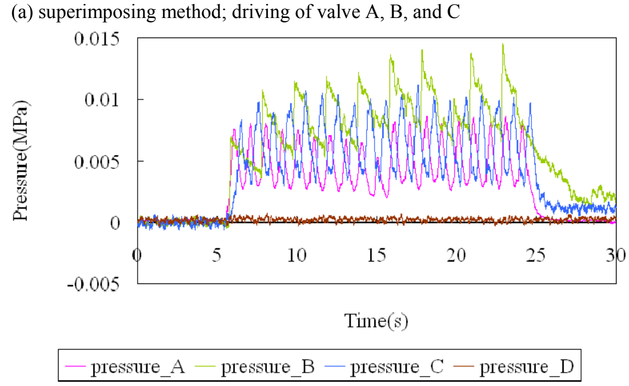
(a) superimposing method; driving of valve A and C



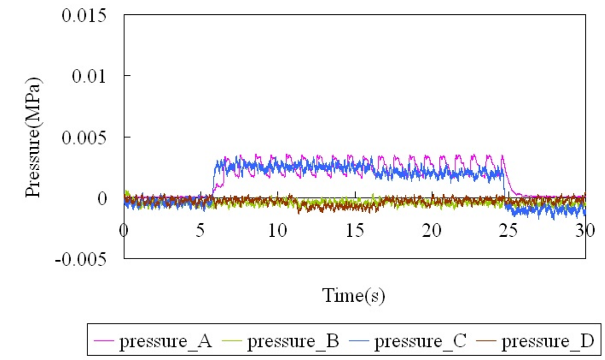
(b) time-sharing method; driving of valve A and C
Figs.11 Experimental results of 2 valves driving



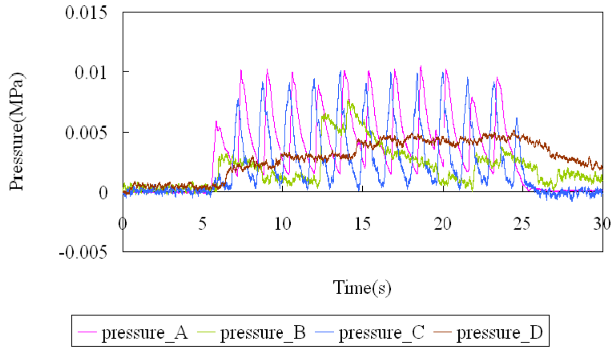
(a) superimposing method; driving of valve A, B, and C



(b) time-sharing method; driving of valve A, B, and C
Figs.12 Experimental results of 3 valves driving



(a) superimposing method; driving of all valves



(b) time-sharing method; driving of all valves

Figs13 Experimental results of all valves driving

V. Control of Multi-DOF Pneumatic System

The prototype valves and time-sharing method are applied to an experimental pneumatic system with four pneumatic cylinders as shown in Fig.14. These pneumatic cylinders are double-acting cylinders and the works of 220 [g] are mounted on the cylinders. Time-sharing method is applied because it works better than superimposing method especially for 3 and 4 valve drives as shown in Chapter Ⅳ. The pressure of the port for expanding the cylinder is controlled by the valve.

The experimental results are shown in Fig.15, where typical driving cases are shown. The control parameters of the oscillator signal such as amplitude and the cycle time of time-sharing are experimentally decided as shown in Tab.2. The displacement of the cylinder rod is measured by a motion capture system.

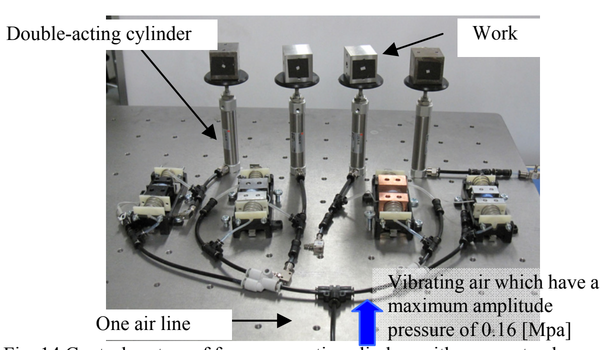
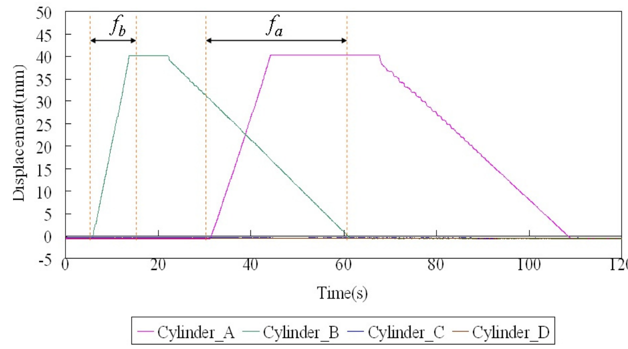
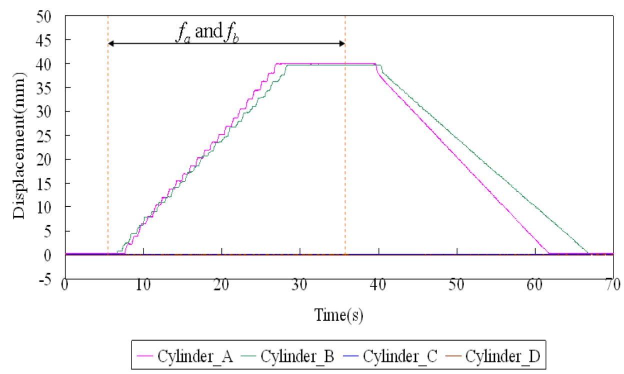


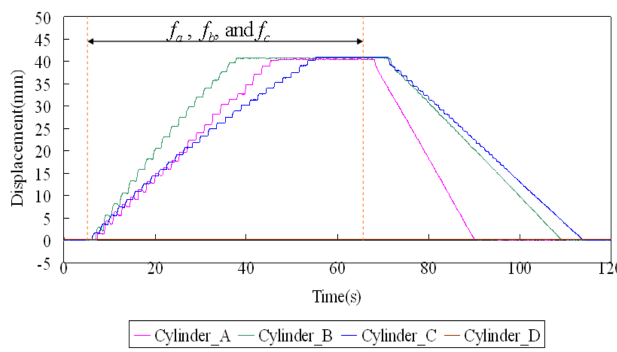
Fig. 14 Control system of four pneumatic cylinders with resonant valves



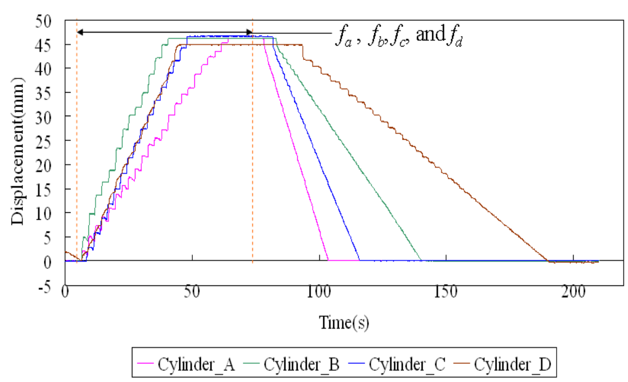
(a) single cylinder driving; driving of cylinder A after driving cylinder C



(b) 2 cylinder driving; A and C



(c) 3 cylinder driving; A, B, and C



(d) all cylinder driving

Fig.15 Control results of four pneumatic cylinders with resonant valves

TABLE 2 THE PARAMETER OF INDEPENDENT CONTOROL SIGNAL

Control cylinder	f_n(Hz)	Amplitude pressure (kPa)	T_n(msec)
single-cylinder	10.5	160	----
	15	160	----
2-cylinder	10.5	160	500
	15	97	400
3-cylinder	10.5	34	400
	15	34	400
	26.5	126	1000
all-cylinder	10.5	97	800
	15	34	400
	26.5	34	200
	20	160	1200

As these results show independent control of four pneumatic cylinders using the time-sharing method is successfully realized. The error of the displacement comes almost from calibration error of the motion capture.

VI. CONCLUSION

In this research, a new pneumatic control method for multi-DOF pneumatic systems that achieves downsizing of the pneumatic valves and the entire system is proposed.

This new method can control many pneumatic cylinders independently by giving air vibration signals to air supply line. It needs no electrical wires and multi-pneumatic lines, making pneumatic system with multi-DOF free from spaghetti-like tubes and wires. The multiplex pneumatic transmission system consists of the valve, the oscillator, and air tube only.

A new prototype valve is developed for this system. A key point of the prototype valve is a valving element which is the rubber button valve. The rubber button valve is manufactured by a simple process of rubber molding and excimer bonding.

A multi-valve driving method called the time-sharing method is also proposed for driving several valves at the same time. This method was compared with the superimposing method, proposed in a previous paper. The experiments show that this new control method works better than the previous method especially for driving many actuators at the same time. In the experiment using the time-sharing method, multiplex driving of the four valves was confirmed. In future tasks, optimization of the cycle time of each frequency will be investigated in the time-sharing method.

The control of multi DOF pneumatic system with resonant valves without electric wires has been realized in the experiments. The four pneumatic cylinders are controlled independently using time-sharing method. This multiplex pneumatic control system is effective to the multi-DOF pneumatic systems.

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