Self-Excited Vibration Valve That Induces Traveling Waves in Pneumatic Soft Mobile Robots

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***Abstract*—This letter presents a soft compact valve inducing self-excited vibration to be aimed for simplification of piping, power saving and downsizing the total system for pneumatic soft mobile robots generating traveling waves. The presented device is composed of flat tubes, permanent magnets, and restraint parts. It is capable of switching the inner pressure among three isolated chambers alternately and periodically by using the constant air pressure supplied from a single line. In this letter, we describe the driving principle of the valve to switch different chambers automatically, while detecting the pre-set pressure inside each chamber without sensors. The prototype has a flexible sheet structure with a mass of 5.1 g and a thickness of 10 mm, and was examined to induce a self-excited vibration of 0.6 Hz by air supply of 80 kPa. Moreover, it was also confirmed that when the developed valve was mounted on a flexible seat-type mobile, it was possible to propel through a narrow space with 25 mm gap smoothly while generating traveling waves. Finally, the effectiveness of the proposed valve is discussed through the experimental results.**

***Index Terms*—Soft robot materials and design, hydraulic/pneumatic actuators.**

I. INTRODUCTION

THE use of traveling waves inspired by natural creatures such as snakes, snails, and earthworms is one of the effective mobile methods in special environments such as narrow terrain and fragile ground that are difficult to move by wheels and crawlers. In particular, the generation of traveling waves by pneumatic soft actuators is promising because it has the potential to exhibit both excellent ground adaptability due to its flexible structure and high output/weight ratio drive [1]–[3].

To generate traveling waves by air pressure, it is necessary to pressurize and exhaust three or more actuators with a certain phase difference. To achieve this, generally, it is necessary to connect the same number of pressure supply tubes and valves as that of actuators, which leads to reduce the flexibility of the robot body or hinder its movement [4]–[13]. In addition, as the pressure supply tube becomes longer, energy consumption increases and the response becomes slow. In the structure with all valves stored in the robot main body, the electric cables to drive valves, or valves themselves tend to lose flexibility and mobility of the robot.

Manuscript received September 10, 2019; accepted January 26, 2020. Date of publication March 4, 2020; date of current version May 13, 2020. This work was supported by JFPS KAKENHI under Grant JP19H02105. This letter was recommended for publication by Associate Editor J. Rossiter and Editor A. Okamura upon evaluation of the reviewers' comments. *(Corresponding author: Hideyuki Tsukagoshi.)*

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Digital Object Identifier 10.1109/LRA.2020.2978455

As a method for driving multiple pneumatic actuators individually with reducing the number of pipes, Marchese *et al.* developed an energy-efficient valve using electric permanent magnets [14]. Mosadegh *et al.* developed a device that can control 32 actuators simultaneously using a microfluidic circuit [15]. Nishioka *et al.* developed a valve that opens and closes according to the frequency of the sound wave applied to the working fluid [16]. Bandpass valves that open and close only at a certain pressure were proposed [17], [18]. These methods could control multiple chambers with a single supply line by designing the applied sound wave or pressure signal. However, since the devices tend to increase in size and were composed of rigid structure, it would be difficult to mount them on the soft mobile robot without losing the flexibility.

Research focused on miniaturization was also reported. The soft microfluidic oscillation circuit developed by Mosadegh *et al.* was able to generate an oscillatory output flow when Newtonian fluid was supplied at a constant pressure [23]. Although this circuit was small enough to be mounted on the robot body, the flow rate and pressure were small, and some problems to be apply to mobile robots were remained. To improve it, Wehner *et al.* developed a fully flexible autonomous soft robot that realized high output by converting liquid H_2O_2 into gaseous O_2 inside the robot [24], [25]. However, the switching frequency is 0.1 Hz or less, and there remains a problem of speed improvement for use in mobile robots.

Therefore, aiming at simplification of piping by the simple, small and flexible structure, the authors have been focusing a self-excited vibration type pneumatic drive system that induces vibration and periodically switches the inner pressure of multiple pneumatic actuators with fast speed (Fig. 1).

From this point of view, we previously proposed a small and flexible "self-excited vibration type flexible valve" with a mass of about 1g consisting of a flat tube, restraint, permanent magnet, and holder, and streamlined the pneumatic drive system was realized. The principle is that when a pressure source is connected to the input side of the vibrator and an actuator is connected to the output side, the magnet vibrates while the flow path of one flat tube is blocked by the restraining part, and a periodic pressure increase/decrease operation occurs in the actuator. This configuration has already been confirmed to be effective for switching between two chambers [19].

In this letter, after the basic principle of the self-excited vibration is described, a new configuration that can be connected to n ports ($n \geqq 3$) are presented. The characterization and design methods of the valve are also described. Experimental results

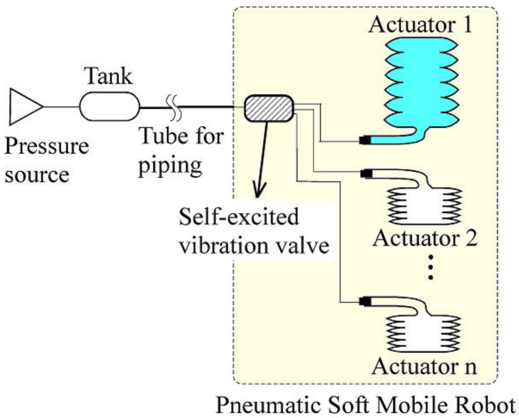

Fig. 1. Concept of simplified pneumatic switched by a self-excited vibration valve.

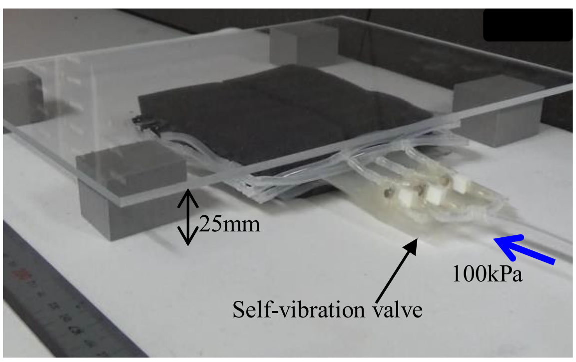

Fig. 2. Sheet-type pneumatic soft mobile robot equipped with a self-vibration valve.

show that the prototype can periodically switch the internal pressure among three pneumatic actuators. Moreover, a flexible seat-type mobile propelling with travelling waves by the prototype is presented and the validity of the proposed method is discussed (Fig. 2).

II. Driving Principle

A. Basic Principle of Self-Excited Vibration

Before explaining the driving principle of more than 3 chambers, the basic principle of self-excited vibration in 2 chambers is introduced.

As a valve of inducing the self-excited vibration supplied from continuous air pressure, we pay attention to the combination of magnets and flat tubes in order to simplify the configuration. A flat tube is a flexible tube, whose cross section has a flat shape in non-pressurized condition and it deforms to approach a circular shape in pressurized condition while keeping a constant cross sectional circumference.

As shown in Fig. 3, the valve is composed of two flat tubes with small exhaust holes, a restraint that bundles them together to limit the bulge of flat tubes to a certain extent, and three permanent magnets. Magnets A and B are fixed to flat tubes A and B, respectively, while Magnet C can move between them. Magnet C works to switch the exhaust state, while the restraint works to block the flow path of the flat tube on the side where

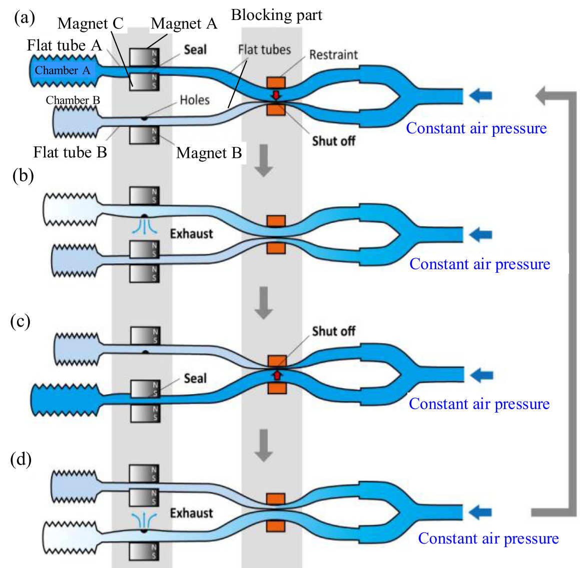

Fig. 3. Basic driving principle of self-excited vibration induced by flat tubes and pneumatics.

the hole is not sealed. Furthermore, the input port of flat tubes is sheared, while the tip of each flat tube is connected to different chambers A and B.

Assume that Magnet C presses against the flat tube A and the hole of it is sealed in the initial condition. When pressurizing from the input port with constant air pressure p_{s} the internal pressure p_A in the chamber A increases, and the cross section of the flat tube A approaches a circle. As a result, the flat tube B is pressed by the flat tube A at the restraint, and the flow path to the chamber B is blocked, which leads to the decompressed condition in the chamber B (Fig. 3(a)). In this state, two kinds of force act on Magnet C. One is the force F_p that works to move it away from the flat tube A by the pressure p_A, and the other is the magnetic force F_M to press it against the flat tube A. Here, the condition of $F_p < F_M$ is satisfied.

When p_A rises further and reaches the switching pressure p_{switch} to hold $F_p > F_M$, Magnet C moves to the flat tube B at once. At the same time, p_A drops due to the exhaust from the hole in the flat tube A (Fig. 3(b)). Similarly, the hole of the flat tube B is sealed, and p_B starts rising (Fig. 3(c)). When it reaches p_{switch}, Magnet C moves to the flat tube A with the exhaust of air from chamber B (Fig. 3(d)). By repeating the above movement automatically, two chambers are periodically pressurized and decompressed by the constant pressure supply, which is the self-excited vibration. Since the switching pressure p_{switch} is determined by the balance between F_p and F_M, it can be kept constant regardless of the change of the supplied pressure and the load on chambers.

B. ON/OFF Control of Self-Excited Vibration

In the valve introduced in the previous section, the ON/OFF state of the self-excited vibration can be controlled by the following principle.

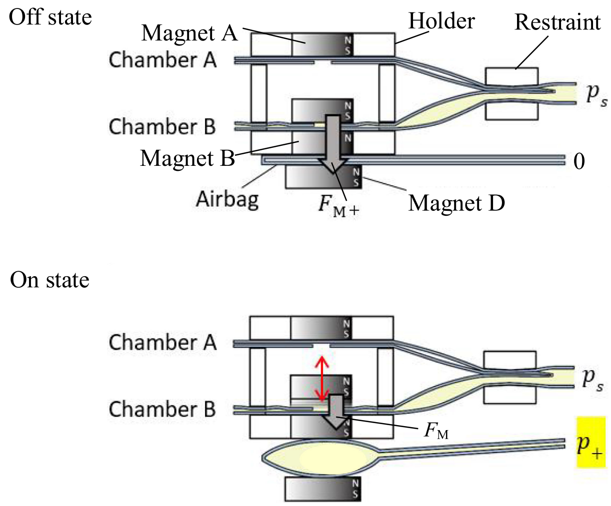

Fig. 4. Structure of a valve with the function of ON/OFF control of self-excited vibration by the pressure supplied to an air bag.

As shown in Fig. 4, Magnets A and B are stored in a holder. The fourth magnet, Magnet D, is added to the side of the chamber B to sandwich a thin airbag with Magnets B. While no pressure is applied to the airbag (hereinafter referred to as "Off state"), the magnetic force F_{M+} acts on Magnet C, which holds the condition of $F_{M+} > F_M$ because of the increase of the magnetic force by Magnet D. Therefore, to detach Magnet C from the flat tube B, the chamber B needs to be pressurized by the pressure $\overline{p^B_{\rm switch}}$. As long as the input port is pressurized by $p_{\rm s}$ smaller than $\overline{p^B_{\rm switch}}$, no vibration arises.

On the other hand, when the trigger pressure p_+ is applied to the air bag, it swells and Magnet D leaves from Magnet B (hereinafter referred to as the "On state"), which leads to the decrease of the magnetic force on Magnet C. As soon as it reaches F_M holding $F_M < F_p$ and the pressure in the chamber B becomes $p_{\rm switch}$, Magnet C starts moving to the flat tube A and then the self-excited vibration arises. When the supply pressure $p_{\rm s}$ is set so that it satisfies $p_{\rm switch} < p_s < \overline{p^{\rm B}_{\rm switch}}$, the ON/OFF state of vibration can be controlled depending on whether p_+ is applied or not.

C. Principle of Three Actuator Switching

The self-excited vibration among three actuators can be induced by combining the valves with ON/OFF control function, introduced in the previous section.

These three valves are arranged in parallel for the same supply line. In each valve, the port A is connected to both an actuator driven directly and an air bag to work as a trigger for the next step, while the port B is closed (Fig. 5(a)). The pressure in Actuator 3 is fed back to Valve 1. Due to this configuration, the internal pressure of the port A in each valve can be transmitted to the airbag in the next step as the trigger pressure p_+.

In the initial state, shown in Fig. 5(a), Magnets C in all valves are attached to the flat tube B by the force of Magnet D. Immediately after the input port is pressurized by $p_{\rm s}$, the ports B in all valves begin to be pressurized, while the ports

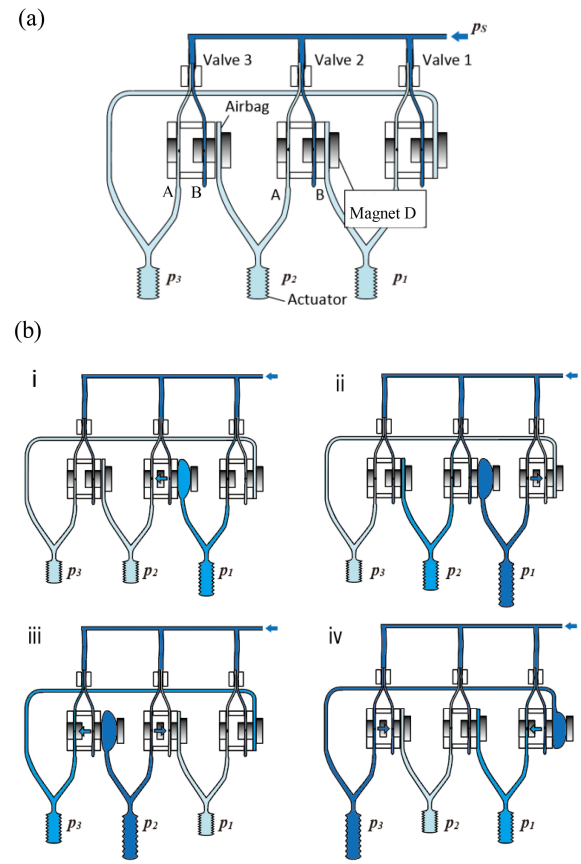

Fig. 5. Basic principle of valve system switching three or more chambers.

A are not pressurized. As the first step, while the pressure in the port B is increasing, Magnet C in Valve 1 with the largest pressure-receiving area moves to the port A, which leads to start pressurizing both Actuator 1 and the air bag in Valve 2. The moment the pressure in the air bag reaches p_+, Magnet C in Valve 2 starts to move (Fig. 5(b)-i). In Actuator 1, when p_1 reaches $p_{\rm switch}$, Magnet C in Valve 1 returns to the port B, resulting in decompressing Actuator 1. At the same time, Actuator 2 begins to be pressurized (Fig. 5(b)-ii). Similarly, in Actuator 2, soon after p_2 reaches $p_{\rm switch}$, Magnet C in Valve 2 returns to the port B to decompress Actuator 2 (Fig. 5(b)-ii). The same motion also arises in Actuator 3, and when p_3 reaches $p_{\rm switch}$, it begins to be exhausted, after the airbag in Valve 1 is pressurized by p_+. These are a cycle of self-excited vibration.

The time transition of the pressure among three chambers can be illustrated as shown in Fig. 6. By changing the trigger pressure p_+, the overlap ratio between two chambers cam be adjusted. If the flow rate on the supply side is too large and $p_{\rm s}$ exceeds $\overline{p^{\rm B}_{\rm switch}}$, the magnets of all valves will move to the side A, and the above-mentioned synchronous operation will not occur.

III. Design Method

Considering the balance of forces acting on the central magnet, the switching action is caused by the force F_p due to the internal pressure of the flat tube exceeding the force F_M due to the magnetic force. In other words, switching occurs when

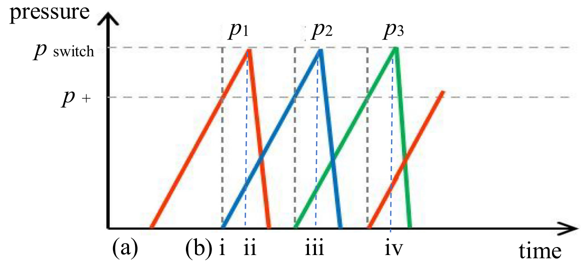

Fig. 6. Image of the time transition of the pressure among three chambers. The label of each state of time fits together with those in Fig. 5.

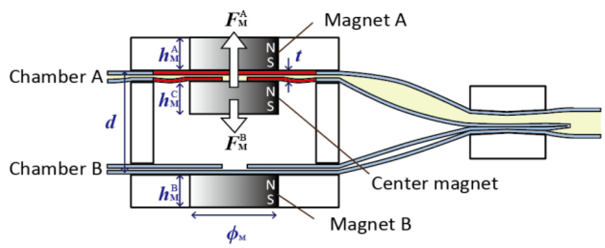

Fig. 7. Mechanical balance between the attached force by magnets and the detached force by the pressure inside the pressure.

Equation (1) is satisfied.

$$F_p \geq F_M \tag{1}$$

Therefore, we will consider dynamically how F_M and F_p change depending on the valve design parameters.

Naturally, if the magnetic force is increased by increasing the height of the magnet, the attractive force F_M will increase. F_M depends not only on the strength of the magnetic force but also on the distance d between the magnets AB and the thickness t of the flat tube, as shown Fig. 7. As t increases, F_M^A decreases, so the adsorption force F_M decreases. On the other hand, as d increases, F_M^B decreases, so the adsorption force F_M increases. However, if d is too large, even if the flat tube expands, the central magnet does not move to the opposite side, and self-excited vibration does not occur. Therefore, F_M can be expressed by Equation (2).

$$F_M = F_M^A - F_M^B \tag{2}$$

As F_M rises, F_p required for the switching action increases, so the switching pressure rises. In other words, when designing a valve with the target switching pressure as small as possible, it is considered effective to reduce the thickness t of the flat tube. F_p is the resultant force of the tube's internal pressure directly pushing the magnet and the tension T applied to the magnet by the expansion and deformation of the flat tube. The force with which the internal pressure directly presses the magnet is $p \cdot S_M$, where S_M is the cross-sectional area of the magnet, which leads to the following relationship.

$$F_p = pS_M - T \tag{3}$$

On the other hand, the tension T changes depending on the posture of the flat tube. Therefore, in order to improve the reproducibility of the switching operation, a slit that does not block the flow path was provided in the case and fixed by inserting two flat tubes in the slit. Let the fixed length of this tube be l. By this fixing, the expansion deformation of the flat tube outside the case does not affect the tension T. In other words, only the deformation of the tube in the case needs to be considered when clarifying the relationship between each parameter and F_p.

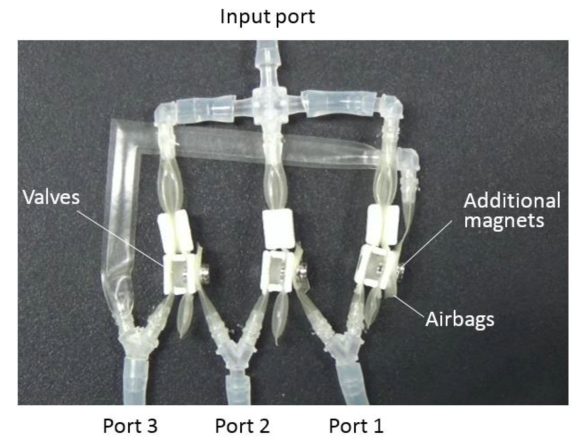

Fig. 8. Developed 3 ports self-excited vibration valve capable of inducing traveling waves by the constant air pressure.

TABLE I
SPECIFICATION OF THE PROTOTYPE OF THE VALVE

Number of output ports	3
Mass	5.1g
Size	80 × 50 × 10mm
Size of magnets used in valves	$\phi 3 \times 1$ mm
Size of additional magnets	$\phi 4 \times 2$ mm

IV. EXPERIMENT

A. Developed Valve

By connecting three self-excited vibration valves, a flexible valve seat that periodically pressurizes and depressurizes the three chambers was fabricated. Fig. 8 shows the appearance of the flexible valve seat, and Table I shows the specifications. A flat tube with a thickness of 0.2 mm and a width of 4 mm was used, and the magnet fixture and restraint were made by 3D printing of ABS resin. The dimensions are as thin as 80 × 50 × 10mm, and the weight is as light as 5.1g. The valve magnet fixtures, restraints, and magnets have a rigid structure, but are basically flexible tube structures that can be mounted on seat-type soft robots.

B. Self-Excited Vibration Among Three Pneumatic Actuators

Three flexible actuators were mounted on the manufactured flexible valve seat and a drive experiment was conducted. The pneumatic actuator used was a WTA (Wound tube actuator) that expands under pressure [29]. Fig. 9 shows the movement of each actuator switched by the developed valve. The prototype

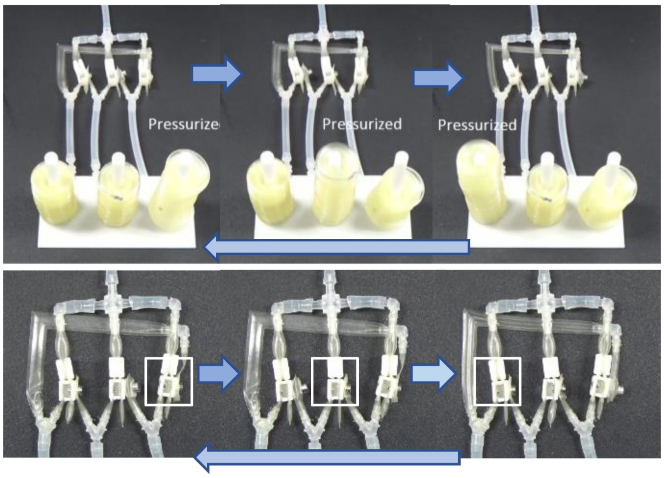

Fig. 9. Soft sheet device switching pressure modes of three pneumatic actuators cyclically.

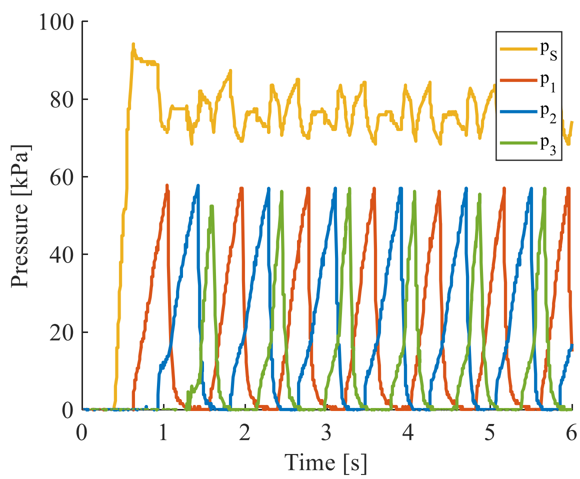

Fig. 10. Time transitions of the pressure in the experiment.

with seat structure could realize the pressure increase/decrease operation of the three actuators periodically only by supplying a constant pressure of 100 kPa. In order to analyze the switching action of the flexible valve seat, the time transition of the internal pressure of each chamber and the supply pressure were measured with a pressure sensor. Fig. 10 shows the measurement results. We made sure that the switching pressure of each actuator could be successfully kept within range of 55–58kPa, although the air pressure just before the valve changed.

C. Installation on the Sheet-Type Mobile Robots

The effectiveness of the proposed method was demonstrated by mounting a flexible valve seat that periodically pressurizes and depressurizes three chambers on a seat-type mobile robot that generates traveling waves, whose basic structure was previously reported in [6].

Fig. 11 shows the driving principle of the robot, which consists of a polyurethane sheet and a polyurethane foam. Inside the polyurethane sheet, the flattened chamber sets A, B, and C are arranged in two layers. First, in Step 1, chamber sets A are

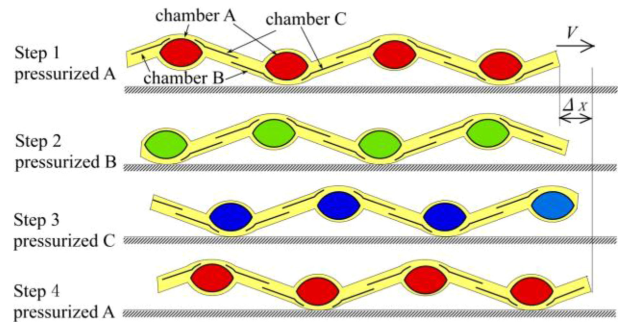

Fig. 11. Driving principle of the sheet-type robot composed of three pneumatic chambers.

TABLE II
SPECIFICATION OF THE SHEET-TYPE MOBILE ROBOT

Mass	46.2 g
Size	160 × 140 × 20 mm
Pressure	50-100kPa

pressurized by pneumatics. When the pressure chambers above the central axis of the polyurethane sheets are pressurized, the sheet bends such that the bottom becomes convex, and when the pressure chambers below the central axis are pressurized, the sheet bends such that the top becomes convex. The overall sheet deforms into a sine-like wave by repeatedly alternating the top and bottom convex deformations.

Next, in step 2 when the chamber sets B are pressurized, a sine-like wave whose phase advances by $2\pi/3$ is generated, and the robot moves forward in the same direction as the wave propagation direction. In step 3 when the pressure chamber C is pressurized, a sine-like wave advanced in phase by $2\pi/3$ is generated, and the robot moves further forward. The velocity V is given by a simple multiplication of the wave frequency f by the stride length Δx, as follows.

$$V = f\Delta x \tag{4}$$

The specification of the developed sheet-type mobile is as shown in Table II. The propulsion experiment was conducted by mounting the flexible valve seat on the back of the mobile robot. The three chambers could be switched automatically by constant air pressure. As shown in Fig. 12, applying a constant pressure of 100 kPa from one supply tube to the seat valve enabled the robot to go forward by generating the traveling waves.

Fig. 13 shows the experimental results of the transition of frequency and locomotion speed, when the supply pressure altered. Both of them increased as supply pressure increased, since the flow rate flowing to each chamber also increased. However, they didn't change linearly. Under the supply pressure of 50 kPa, no vibration occurred, because the switching pressure to let the magnet detach from the flat tube was designed to satisfy over 52 kPa. From these experiments, we can say that the frequency and locomotion speed are adjustable by supply pressure to the proposed valve. Supply pressure of 60 kPa arose

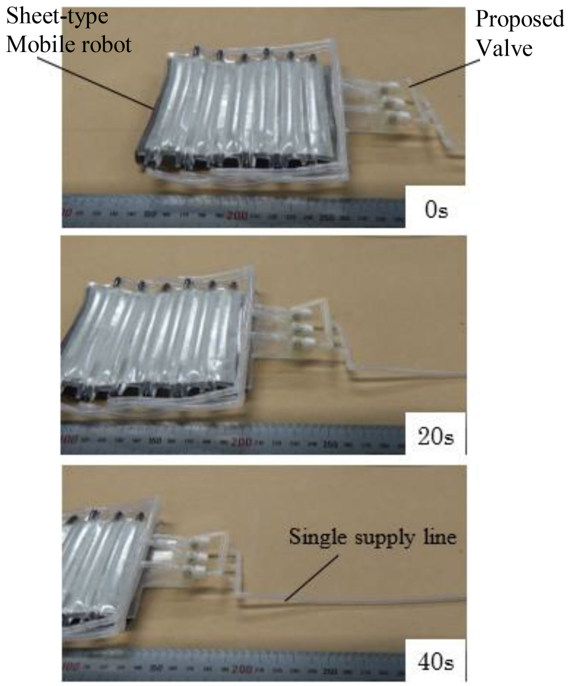

Fig. 12. Proposed sheet device enables the actuator to propel by supplying constant air pressure from single supply line.

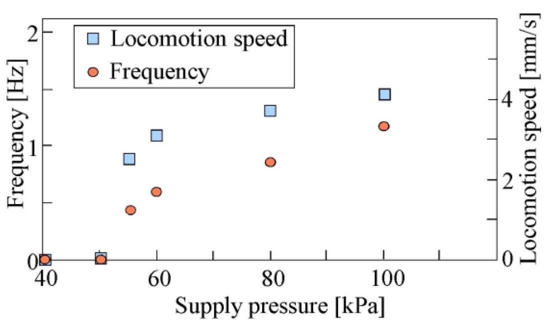

Fig. 13. Experimental results showing the transition of frequency and locomotion speed adjusted by supply pressure.

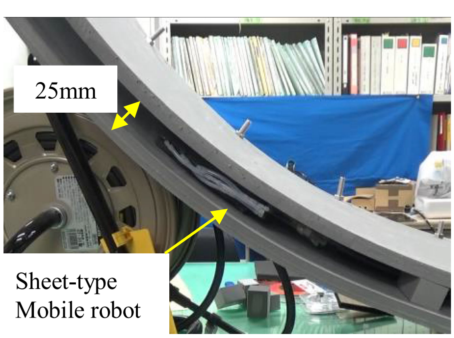

Fig. 14. Propulsion experiment in narrow gap.

the frequency of 0.6 Hz and the locomotion speed of the actuator was 3.2 mm/s.

Next, a propulsion experiment in a curved and inclined gap was performed as shown in Fig. 14. The width of the gap is 25 mm. Generally, when a soft robot promotes a narrow environment, it is difficult to propel a long distance because an external

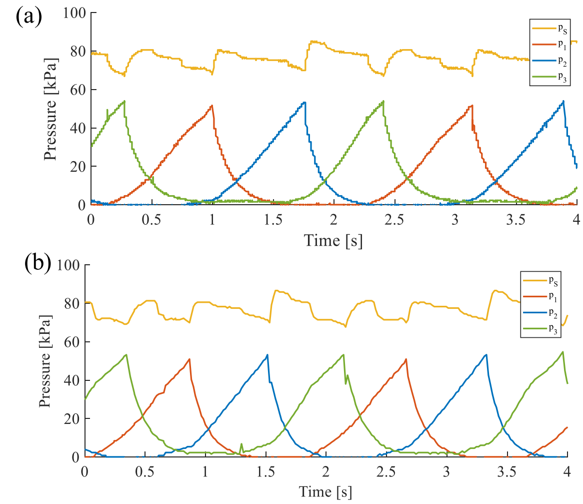

Fig. 15. Time transitions of the pressures in the experiments. (a) Size of airbags are 7 × 7 mm (b) Size of airbags are 8 × 8 mm.

control device is installed to allow the actuator to enter the gap together with multiple supply tubes. In this experiment, by installing a flexible valve seat thinner than the actuator in the robot body, it is possible to generate traveling waves with only one supply tube for supplying compressed air. Due to these thin, flexible and simple structure, as shown in Fig. 12, propulsion within the gap of the entire mechanism was realized. In addition, since the valve is mounted on the robot body, the pressure wave only needs to be able to propagate only to the part ahead of the valve, so the frequency does not decrease during long-distance propulsion.

V. Discussion

The overlap ratio between two chambers can be flexibly designed by adjusting the trigger pressure p_+.

The pressure p_+ at which the air bag pulls off the additional magnet is determined by the magnetic force of four magnets A, B, C, and D, and the size of the air bag. However, if the magnetic force of the valve body magnet or the additional magnet is changed, the switching pressure will also change. On the other hand, the value of p_+ can be adjusted independently of the switching pressure by changing the size of the airbag. In other words, we can say the switching pressure and overlap ratio can be designed independently.

With respect to the manufactured valve seat, the time transition of pressure was measured by changing the size of the airbag between 7×7 mm and 8×8 mm. Both measurements were performed under the same conditions of supply pressure and supply flow rate. As shown in the experimental results in Fig. 15, although the switching pressure has not changed, the pressure p_+ required to pull away the magnet decreases as the pressure-receiving area of the airbag increases. For this reason, it can be confirmed that the overlap rate is high and the switching cycle is short.

VI. Conclusion and Future Work

We proposed a method of switching the pressure increase/decrease of three or more chambers with only constant pressure supply by synchronizing multiple flexible small valves that induce self-excited vibration. The developed flexible valve seat realized periodic pressure increase/decrease operation of three pneumatic actuators. A flexible valve seat is mounted on a flexible seat-type moving body that generates traveling waves, and propulsion in a narrow environment with single-wire input is realized, and the effectiveness of the proposed method is verified.

In the future, we plan to establish a detailed design method of switching pressure and to examine the method of reversing the switching order, and to apply it to a wider variety of soft robots.

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