Self-Excited Air Flow Passage Changing Device for Periodic Pressurization of Soft Robot

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RESEARCH

Self-Excited Air Flow Passage Changing Device for Periodic Pressurization of Soft Robot

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Abstract

Recently pneumatic-driven soft robots have been widely developed. Usually, the operating principle of this robot is the inflation and deflation of elastic inflatable chambers by air pressure. Some soft robots need rapid and periodic inflation and deflation of their air chambers to generate continuous motion such as progress motion or rotational motion. However, if the soft robot needs to operate far from the air pressure source, long air tubes are required to supply air pressure to its air chambers. As a result, there is a large delay in supplying air pressure to the air chamber, and the motion of the robot slow down. In this paper, we propose a compact device that changes its airflow passages by self-excited motion generated by a supply of continuous airflow. The diameter and the length of the device are 20 and 50 mm, respectively, and can be driven in a small pipe. Our proposed in-pipe mobile robot is connected to the device and can move in a small pipe by dragging the device into it. To apply the device widely to other soft robots, we also discuss a method of adjusting the output pressure and motion frequency.

Keywords: Self-excited valve; In-pipe robot; Soft robot

1 Introduction

The advantages of a pneumatically actuated device are not only its high power-to-weight ratio but also the absence of any mechanical elements that use electromagnetic force at the end effector of the device. Therefore, it can be used in a combustible gas environment because it does not generate sparks electrically. It can contact a human safely because electric leakage is not possible [1, 2]. If the device is fabricated from non-magnetic material such as plastics, it can potentially be utilized in an MRI environment [3, 4]. Moreover, if the device incorporates many elastic inflatable chambers, it can generate complicated motions and have high passive adaptability [5, 6]. Such robots are called soft robots. A soft robot with high passive adaptability allows contacting complicated-shaped objects or fragile objects without the need for complicated control [7]. Of course, there are other operating principles of soft robots, such as chemical reactions or static electricity, but pneumatic actuation is realistic for practical use for now [8].

The operating principle of many pneumatic-driven robots uses periodic inflation and deflation of the air chambers inside them. If the motion is simple, such as the opening and closing motion of a robot hand, it can be driven by an air chamber supplied by a single air pressure source [9]. However, to generate continuous motion, such as the locomotion of a mobile robot or the rotation of a pneumatic-driven motor, some chambers that can be inflated and deflated periodically are required [3,

4, 10, 11, 12, 13, 14]. Therefore, these air chambers in such devices are equipped with individual air tubes that supply air pressure to the air chambers. Usually, the air pressures supplied to the air tubes are independently controlled by solenoid valves. For some soft robots, such solenoid valves need to be placed far from the workspace. For example, an in-pipe locomotive device cannot be equipped with solenoid valves because the solenoid valves are too large for the pipe. Further, a solenoid valve can generate electric sparks. Thus, it cannot be used near a gas pipe. Moreover, the pneumatic-driven motor developed for use under an MRI environment cannot utilize an electromagnetic device near the workspace. In such cases, long air tubes are required to drive the robot. This causes a large delay in the inflation and deflation of the air chambers because of the compressibility of air. As a result, the soft robot cannot generate quick motion. In such cases, a self-excited mechanism that can be driven by continuous airflow is effective. Some self-excited pneumatic-driven devices have been developed. Pneumatic-driven motors that generate continuous rotational motion and can be used just like an electric motor have been developed [15, 16]. A simple mechanism that uses the buckling motion of a bent tube to generate a self-excited vibration motion has been developed [17]. To supply air pressure to two different air chambers periodically, a device that uses a periodic jump of a magnet has been developed [18].

We are proposing a soft robot called a bundled tube locomotive device [19, 20, 21]. It is composed of several inflatable tubes that are bundled and periodically inflated and deflated. The tubes are bundled into helically twisted, 3-braided, or 6-braided shapes, and the device generates a helical rolling motion or winding motion based on its bundled shape and the sequence in which the tubes are inflated to move inside a narrow pipe. Its body has high elasticity and adapts against the inside pipe wall passively. Therefore, it can move inside pipes of different diameters and can pass through an elbow part without requiring complicated control. Moreover, the twisted-type bundled tube locomotive device can be fabricated by an extrusion molding machine continuously. Therefore, it is suitable for mass production, which can lower the device cost, turning it into a disposable device.

On the other hand, if the device becomes long, as shown in Fig. 1(a), its inflatable air chambers also become long, and the amount of air to be supplied increases, too. Thus, both the frequency of the periodic inflation and deflation motion and its progress velocity decrease. In such a situation, connecting a short bundled tube locomotive device to non-inflatable air tubes that supply air pressure to the device is effective, as shown in Fig. 1(b). However, if a pipe to be explored becomes long, the air-supply tube becomes long, too. This causes a large delay in the arrival of the pressure to the front tip of the device and also slows down the frequency of the periodic motion. To overcome this problem, a device that can be dragged inside the pipe and driven by continuous airflow to switch its output port periodically by self-excited motion, as shown in Fig. 1(c), is effective. However, the existing self-excited devices [17, 18] cannot be used for devices that need to change more than three output ports. Therefore, in this paper, we have proposed a compact self-excited airflow passage changing device that can be dragged into a pipe to drive our bundled tube locomotive device.

The rest of this paper is organized as follows. In Section 2, we explain the mechanism and self-excitation principle of the device. In Section 3, we describe the

experimental confirmation of the characteristics of the device. In Section 4, based on the experimental results, we discuss the method to adjust the output pressure and self-excitation frequency, and the actual soft robot is connected to the developed device to confirm that the device can operate an in-pipe mobile soft robot. In Section 5, we provide concluding statements and outline future plans.

2 Method of Self-Exciting

The developed self-excited flow passage changing device is shown in Fig. 2. It has an input port and three output ports on opposite sides of the cylindrical body. By applying air pressure to the input port, the device periodically changes the airflow passage inside it to switch between the output ports. The bundled tube locomotive device is connected to the output ports, and its air chambers are inflated and deflated periodically. Three concentric cylinders are arranged inside the cylindrical body, which also houses three plungers. The heads of the plungers project to the input port side as shown in Fig. 3 and they are pushed against an inclined circular plate. The plate is made of Teflon to minimize friction and has a bowl-shaped cavity. The cavity fits to a ball attached to the pipe of the input port so that the plate can rotate freely around the center of the ball. Therefore, when one plunger extends and pushes the plate up, the plate pushes down two other plungers, contracting them. Fig. 4 shows the cross section of an elbow part of a 25A pipe and the size of the device [22]. The device is designed to pass through the elbow part, and the diameter and length of the main cylindrical part are 20 and 40 mm, respectively.

Three concentric cylinders are arranged inside the device. The schematic diagram of a cross section of a plunger is shown in Fig. 5, where (a) and (b) show the plunger in the contracted and extended, respectively. The cylinder has an input port that is connected to an air pressure source, two relief ports R_1 and R_2 that are released to atmospheric pressure, and three connecting ports P_1 , P_2 , and P_3 that are connected to the other cylinders. When the plunger is contracted as shown in Fig. 5(a), the plunger is not moved by the air pressure, and the pressure at port P_1 becomes high. When air pressure is applied to port P_3 , the plunger is pushed up as shown in Fig. 5(b), and the pressure at port P_2 becomes high.

Fig. 6 shows the working principle of the device. The first suffix indicates the number of the cylinder, and the second suffix denotes the number in the port name, as shown in Fig. 5. In reality, three concentric cylinders, C_1 , C_2 , and C_3 , are arranged, but in this figure, they are drawn schematically. Therefore, the flow channels of the right end α and β are connected to the flow channels of the left end α and β . From now on, n denotes the cylinder number, and $n+1$ and $n-1$ denote the neighboring cylinder numbers. However, in the case of $n=3$, $n+1$ denotes cylinder number 1, and in the case of $n=1$, $n-1$ denotes cylinder number 3. P_{n1} and $P_{(n-1)3}$ are connected by flow channel $F_{n(n-1)}$. P_{n2} and output port $O_{(n+1)}$ are connected by flow channel $F_{n(n+1)}$. Between port P_{n3} and output port O_n , there is a throttle valve V_n that can narrow the flow channel by tightening a screw. At the output ports, the air chambers of the soft robot are connected.

When the plunger of C_1 is pushed up, plungers of the other cylinders are pushed down by the inclined plate, as shown in Fig. 6(a). The input air pressure from I_1 and I_3 pressurizes tube 2 via P_{12} and P_{31} , respectively. When tube 2 is inflated

sufficiently and the pressure inside it becomes large, the pressure applied to port P_{23} pushes up the plunger in C_2 . In this condition, the applied pressure to I_2 is connected to R_{32} via P_{21} and P_{32} . Therefore, the pressure at P_{13} becomes low. As a result, the plunger of C_2 is pushed up and the plunger of C_1 is pushed down by the inclined plate to reach the state shown in Fig. 6(b). Then, O_2 is connected to R_{12} via P_{12} , and thus tube 2 is deflated. Similarly, when tube 3 is inflated sufficiently, the device changes its state, as shown in Fig. 6(c). By changing its states in this way, the device can generate continuous self-oscillatory motion and change its airflow passage to inflate the three tubes periodically.

Throttle valve V_n is introduced to control the self-excitation frequency. For example, when the state changes from Fig. 6(a) to Fig. 6(b), the plunger of C_1 needs to be pushed down. The air pressure in the cylinder needs to be released to the atmosphere from R_{32} via P_{32} . On the other hand, the air pressure is still supplied from I_2 via P_{21} . Therefore, if the flow line is made narrow by V_1 , the effect of the supplied air pressure from I_2 becomes dominant, and it resists the pushing down of the plunger. As a result, the frequency of the self-excited motion may decrease.

The actual design is shown in Fig. 7. Grooves are dug on the side surface of the cylindrical main part, and they are covered to operate as flow channels. Inside the main part, three holes are drilled from the bottom surface to form the cylinders, and the flow channels and the cylinders are connected by holes drilled from the side surface. At the central axis of the main part, a pipe is inserted and an air tube is connected to supply air pressure. The cross sections of Fig. 7 are shown in Fig. 8. A hole (I_n) is drilled from the side surface that reaches the central axis of the main part so that it connects the input pipe and the cylinders to become input port I_n , as shown in Fig 8(a). Hole (I_n) is closed by the cover so that it does not work. Fig. 8(b) shows the cross section at relief port R_{n1} . The flow channels connected to R_{n1} are connected to the top surface of the cylindrical main part to evacuate the air. Fig. 8(c) shows the cross section at input port I_n . It is seen that the input ports are drilled from side surface up to the central axis of the main body. Fig. 8(d) shows the cross section at port P_{n3} . Output ports O_n are equipped with tube fittings to connect the soft robot. To help the reader understand the connection of flow channels F_{32} and F_{12} , a cutaway image of output port O_2 is also shown in Fig. 8(e). Flow channel F_{12} and O_2 are connected by hole W_{21} , and flow channel F_{32} and O_2 are connected by hole W_{22} . To control the flow amount in hole W_{22} , a set screw is fitted to work as throttle valve V_2 .

3 Experimental Results

In this mechanism, until the air pressure in the air chamber of the soft robot connected to output port O_n becomes high enough, the air pressure of port P_{n3} that pushes the plunger also remains low, and the plunger does not start to move. When sufficient air is supplied to the air chamber, the pressure that pushes the plunger becomes high, the plunger starts to move, and its airflow passages change. Therefore, the device's frequency of self-excitation may be affected by the volume of the air chamber of the soft robot. To apply the proposed device to many types of soft robots, it should be possible to change the output pressure and the self-excitation frequency arbitrarily without modifying the design considerably.

3.1 Effect of the volume of the air chambers.

First, we confirmed the effect of the volume of the air chambers. In the experiment, we compared its behaviors when non-deformable air chambers of volumes ranging from 0 to 10,000 mm³ are attached to the output ports. The air pressure applied to the input port is 0.4 MPa. Air pressure gauges are attached to the chambers to measure the pressure of the output port. The results are shown in Fig. 9, where (a), (b), and (c) show air chambers of volumes 0 mm³ and 10000 mm³, and the relationship between the volume of the attached air chambers and the frequency of the self-excitation. The output pressures are almost constant at 0.3 MPa, and the frequency decreases when the volume of the air chamber increases, which is in line with our expectations.

3.2 Effect of the flow amount of the supplied air.

We considered that by changing the flow amount supplied to the input port, the self-oscillation frequency will also be changed. We attached a throttle valve to the air-supplying tube and measured the frequencies and the output pressure when the throttle valve is rotated. The supplied air pressure is 0.4 MPa, and air chambers of volume 10,000 mm³ are connected to the output ports. The experimental results are shown in Fig. 10. As the throttle valve is rotated by 4.5 to 5.5 rounds, the frequency and output pressure increase correspondingly, and if the number of rotation rounds exceeds 5, saturation is reached. Moreover, if the number of rotation rounds is smaller than 4, the self-oscillation motion becomes unstable. Therefore, the motion frequency and the output pressure cannot be independently controlled by varying the flow speed alone. Moreover, the controllable range of this technique is small.

3.3 Effect of the pressure of the supplied air.

Next, we varied the input pressure and measured the motion frequency and the output pressure. In this experiment, air chambers of volume 2,000 mm³ are connected to the output ports so that the frequency does not become too slow, which would make the motion unstable. The experimental results are shown in Fig. 11. It is observed that increasing the applied input pressure produces a corresponding increase in the motion frequency and the output pressure. Moreover, if the input pressure becomes lower than 250 kPa, the motion becomes unstable. These results also show that we cannot control the frequency and the output pressure independently by controlling the input pressure alone.

3.4 Effect of the fitted throttle valves.

Next, we measured the effect of the throttle valves fitted between port P_{n3} and output port O_n. We compared the status when the three valves were fully opened with that when the set screws were closed for five rounds that make the valve about half-closed. The experimental result is shown in Fig. 12. We considered that closing the valve may decrease the self-excitation frequency. However, the result shows that when the throttle valve is half-closed, the frequency is not much affected, but the output pressure is clearly increased.

4 Discussion to Adjust the Output Pressure and Self-Excitation Frequency

4.1 Method to independently adjust the output pressure and self-excitation frequency. The experimental results show that the self-excitation frequency and the output pressure can be adjusted independently in the following way. First, set the input pressure so that it is slightly larger than the pressure required to deform the soft robot. Next, by controlling the amount of the input flow, adjust the frequency. Next, by tightening the inner throttle valve, increase the output pressure until it reaches the pressure required to deform the soft robot. If the output pressure cannot reach the required pressure, the input pressure is increased, and the adjusting procedure is repeated. However, the experimental results show that this control method does not have a large controllable range. Therefore, we propose another possible control method, which is described in Appendix.

4.2 Confirm the proposed adjustment method by applying the developed device to a soft robot.

We conducted experiment to confirm that the developed device can drive an actual soft robot. For the soft robot, we used our developed twisted-type bundled tube locomotive device (Fig. 13(a)). The diameter of the device is 6 mm and the cross-sectional design is shown in Fig. 13(b). The device is fabricated by extrusion processing. The developed molding die is shown in Fig. 13(c). Heated polyvinyl chloride (PVC) is extruded from the slit of the die and twisted before the PVC is cooled for curing to form the twisted air chambers. The developed bundled tube locomotive device requires pressure of 250-350 kPa to produce enough deformation to move in a 25A pipe. We connected the bundled tube locomotive device of approximately 30 cm to the self-excited air flow passage changing device, and adjusted the inner throttle valves and the input pressure so that the device can progress in the 25A pipe by trial and error. The device generated a self-excited motion of approximately 4 Hz, and it could move at approximately 20 mm/s by dragging the airflow passage changing device (Fig. 14). On the other hand, it could not pass through the elbow of the 25A pipe, because the tube fittings of the input and output ports of the airflow passage changing device are long, and they got caught at the elbow.

5 Conclusion

The developed self-excited air flow passage changing device succeeded in generating self-excitation motion in line with our expectations. On the other hand, contrary to our expectations, the inner throttle valve did not reduce the frequency, but it increased the output pressure. As a result, we could adjust the output pressure and the self-excitation frequency independently. The developed self-excited air flow passage changing device could drive our soft robot called the bundled tube in-pipe locomotive device, and the robot could make progress in a 25A pipe by dragging the developed device itself into the pipe. However, it could not pass through the elbow part, because its tube fittings are large. In the future, we need to design smaller device including tube fittings so that the device can pass through the elbow part. Moreover, we will introduce additional inner throttle valves at the relief ports so that the device can adjust the output pressure and self-excitation frequency over a larger range and attempt to apply this device to other soft robots for wide use.

Appendix

To control the self-excitation frequency, we also propose another simple method of half-closing the relief ports. If the cross-sectional area of relief port R_{n2} becomes small, it needs a long time to relieve the air that pushes the plunger when the plunger is pushed down, and the frequency is expected to decrease. For the experiment, half the area of relief ports R_{n2} were covered by tape as shown in Fig. 15(a), and the device was assembled. We applied an input pressure of 375 kPa and adjusted the inner throttle valve so that the output pressure becomes 200 kPa. The experimental results are shown in Fig. 15(b). The output pressures are the same, and the frequency significantly decreases when the relief ports are half-closed. Therefore, if a throttle valve is fitted at the relief port, it can control the self-excitation frequency and the output pressure independently over a larger range.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

TT contributes to propose the basic idea and design of the experimental systems.

YS contributes to develop the actual device and conduct the experiments.

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Figures

Figure 1 Problem associated with a long traveling soft robot. (a) Problem associated with long soft robot. (b) Problem when air supply tubes become long. (c) Concept of the self-exciting airflow passage changing device.

Figure 2 Overview of the developed device.

Figure 3 Inclined plate to restrict the motion of the plungers.

Figure 4 Cross section of an elbow part of 25A pipe.

Figure 5 Schematic diagrams of a plunger. (a) The plunger is contracted. (b) The plunger is extended.

Figure 6 Principle of self-excited motion generation. (a), (b), and (c) show the states with plungers in C1, C2, and C3 extended, respectively.

Figure 7 Actual design of the cylindrical main part and its flow channels. (a) Photo of the part. (b) CAD graphic to show the ports and the flow channels.

Figure 8 Cross-sections of the main part. (a) Cylinders and plungers. (b) Cross section at the relief ports. (c) Cross section at the input ports. (d) Cross section to show the connection of the flow channels at output ports. (e) Cutaway image of output port to show the fitted throttle valve.

Figure 9 Frequencies affected by the volume of the chambers. (a) Volume of the attached chamber is 0 mm^3 . (b) Volume of the attached chamber is $10,000 \text{ mm}^3$. (c) Relationship between the volume of the attached air chambers and frequency of self-excitation.

Figure 10 Frequencies and output pressures affected by the amount of the input flow. (a) Relationship between the rotation of the throttle valve and the frequency. (b) Relationship between the rotation of the throttle valve and the output pressure.

Figure 11 Frequencies and output pressures affected by the input pressure. (a) Relationship between the input pressure and the frequency. (b) Relationship between the input pressure and the output pressure.

Figure 12 Effect of the internal throttle valve.

Figure 13 Used soft robot. (a) Cut surface of the actual device. (b) Design of the mold. (c) Developed mold for the extrusion process to make the soft robot.

Figure 14 Experiment to drive the device in a 25A pipe.

Figure 15 Additional method to control the frequency.(a) Relief ports half closed by a tape. (b) Experimental results.

Figures

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