A STUDY ON A SOUND OPERATED VALVE FOR A WEARABLE PNEUMATIC SYSTEM

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ABSTRACT
A sound operated directional control valve (SODC-Valve) is proposed which opens and closes in response to the sound of a specific frequency propagated inside the gas supply tube and therefore needs no electric wiring to convey the control signals. By using multi-frequency sound, several valves can be controlled simultaneously and resultantly the pneumatic multi-degree wearable system can be constructed compactly. Firstly, the sound-gas pressure converter is proposed and improved so that self-excited vibration can be suppressed. Secondly, the basic characteristic of the sound-gas pressure converter is investigated to show that the back pressure is different depending on whether the sound of specific frequency is added or not. Furthermore, a pilot valve is developed. Because the pilot pressure change of the pilot valve developed is only 20kPa, a main valve is proposed and developed. Finally, a pneumatic multi-degree-of-freedom wearable power-assist system is constructed by using a Dry Ice Power Cell as the portable gas supply, wearable actuators developed in the previous study, and two sound operated directional control valves developed. Experimental results show that the sound operated directional control valve is feasible and practical in the pneumatic multi-degree-of-freedom wearable system.

KEY WORDS
Pneumatic, wearable, sound-operated, valve, resonance

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$p_n$</td>
<td>Back pressure of nozzle [kPa]</td>
</tr>
<tr>
<td>$\Delta p_n$</td>
<td>Change of back pressure of nozzle [kPa]</td>
</tr>
<tr>
<td>$p_s$</td>
<td>Supply pressure [kPa]</td>
</tr>
<tr>
<td>$x$</td>
<td>Space between nozzle and head [mm]</td>
</tr>
<tr>
<td>$y$</td>
<td>Displacement of center of head from center of nozzle [mm]</td>
</tr>
<tr>
<td>$z$</td>
<td>Wave length of sound [mm]</td>
</tr>
</tbody>
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INTRODUCTION
Pneumatic power assist multi-degree-of-freedom wearable system has been developed by many researchers. But in most of the traditional pneumatic systems, their focuses are concentrated on the development of actuators [1] [2]. Few of them are argued about wearable power supply sources or valves. Therefore, there exist the problems when the pneumatic systems are used for wearable power assist. For example, the tubes and electrical cords connected between the actuators and valves are troublesome. In
In this paper, a novel valve called Sound Operated Directional Control Valve (SODC-Valve) is developed. The SODC-Valve opens and closes in response to the sound of a specified frequency propagated inside the gas supply tube and therefore needs no electric wiring to convey the control signal for the valve. By using multi-frequency sound, several valves can be controlled simultaneously. Using the previously developed Dry-ice Power Cell [3] as power supply, the SODC-Valve is expected to be used in pneumatic power assist wearable system.

In this paper, firstly, the sound-gas pressure converter is proposed and improved so that self-excited vibration can be suppressed. Secondly, the basic characteristic of the sound-gas pressure converter is investigated to verify that the back pressure is different depending on whether the sound of specific frequency is added or not. Furthermore, a pilot valve of the sound operated directional control valve is developed. Because the pilot pressure change of the pilot valve developed is only 20kPa, a main valve is proposed and developed. Finally, a pneumatic multi-degree-of-freedom wearable system is constructed by using Dry Ice Power Cell as the portable gas supply, wearable actuators developed in the previous study, and two SODC-Valves developed. Experimental results verify that the sound operated directional control valves are feasible and practical in pneumatic multi-degree-of-freedom wearable power assist system.

SOUND-GAS PRESSURE CONVERTER

The SODC-Valve opens and closes in response to the specified frequency sound propagated inside the gas supply tube. If several SODC-Valves are set along the supply tube as shown in figure 1, several actuators can be controlled with the valves simultaneously by adding sound of each valve’s resonance frequency into the supply tube.

Resultantly, the leakage from the nozzle is small when the head stands still. If the head of the vibration element responds to the specified frequency sound in the supply tube and resonates near the nozzle in the arrow direction shown in figure 2, the effective area of flow path out from the nozzle to the atmosphere becomes larger and then the flow rate out from the nozzle becomes larger. As a result, the back pressure \( p_n \) in figure 2 falls down. In one word, if sound is added to the S-P Converter, the head resonates and the back pressure \( p_n \) changes (become smaller). In this paper, the change of the back pressure \( p_n \) is used to make the SODC-Valve open and close.

SELF-EXCITED VIBRATION

In order to investigate the characteristics of the vibration element, sound of a specified frequency is added near the vibration element at the atmosphere. As shown in figure 5, when the frequency of the sound is equal to the resonance frequency of 98Hz, the amplitude of the head reaches the maximum of 1.5mm. If the frequency is set apart from 98Hz with over 1Hz, the amplitude becomes half of the maximum. By using this characteristic, several S-P Converters with different resonance frequency can be controlled simultaneously.
phenomenon of self-excited vibration arises when the supply pressure is added without any sound. When the supply pressure is raised up to 10~20kPa, self-excited vibration starts even though the sound is not added. Once the self-excited vibration starts, it will not stop until the supply pressure is lowered down to about 0kPa. If measures are not taken to solve the self-excited vibration problem, development of SODC-Valve is impossible.

Two methods are found to prevent the self-excited vibration through trial and error. The first one is introducing the overlap to the head in y direction (i.e. vibration direction) which means that the width of the head is larger than the diameter of the nozzle. The second one is introducing the underlap to the head in z direction (i.e. vertical to vibration direction) which means that the nozzle protrudes from the end of the head. The S-P Converter initially developed is adjusted to be zerolap in y direction which means that the diameter of the nozzle is the same with width of the head in order to obtain a larger effective area change of the nozzle when the head resonates. Because of the self-excited vibration, an overlap in y direction and an underlap in z direction are necessary. In y direction, if width of the head is set with 1.2mm which is larger than the diameter of nozzle 0.5mm, in other words, if overlap of 0.35mm is set on both side of the head as shown in figure 4(b), the self-excited vibration does not arise even though the back pressure is raised up to 100kPa in the experiments. It should be mentioned that the overlap should be adjusted to be the minimum. If the overlap is too large, the change of the effective area of the nozzle will become too small. However, the overlap in y direction is not enough. If the sound or disturbance is added, the self-excited vibration will continue unless the back pressure is lowered down to 0kPa even if the overlap is adjusted to very large.

As regards to z direction, the relative position of the nozzle to the head can be adjusted so that the relationship between the nozzle and the head can be change from overlap to zerolap and underlap as shown in figure 5.

In order to investigate the best underlap of z direction, experiment is conducted. The vibration of the head is investigated when disturbance (i.e. touching the head) is added or not. The supply pressure is set as 400kPa and the sound is not added. The result is shown in figure 6. The solid line is the result when no disturbance is added. The position of the nozzle is adjusted from overlap to zerolap and underlap. The back pressure falls down from the position of zerolap. The
fall of pressure is due to the increment of the effective area and not due to vibration. On the other hand, the dashline is the result when disturbance is added at the point A. Because at the point A the position of nozzle is overlap, the disturbance triggers the self-excited vibration of the head to start immediately and the back pressure to fall down to B point. If the nozzle is raised continuously, from point C the back pressure jumps up again to reach D where \( z \) is 0.3mm (i.e. underlap) and the back pressure is the biggest and the self-excited vibration stops. After point D, the dash line follows the solid line. From the result, it is clear that the position of the nozzle \( z \) must be bigger than 0.3mm to ensure that the nozzle is in underlap to suppress the self-excited vibration. On the other hand, it is desired that the underlap of \( z \) is set to be as smaller as possible so that change of effective area of nozzle and the back pressure is big. Therefore, \( z \) should be adjusted to be as near D point as possible.

Using the S-P Converter as shown in figure 2 with the interval \( x \) between nozzle and head adjusted to 0.05mm, overlap on both side of the head in \( y \) direction adjusted to 0.35mm and overlap in \( z \) direction adjusted to 0.05mm, experiments are conducted. The supply pressure is arranged with 4 conditions and under each condition the back pressure is investigated. In the preparation, the back pressure is tuned using the adjustable orifice shown in Figure 2 without any sound. The change of back pressure before and after the sound of 98Hz is added is shown in figure 7. From the results, it is clear that when the supply pressure is set as 400kPa, the back pressure changes from 35kPa when the head does not resonate to 12kPa when the head resonates. Therefore, it is concluded that the maximum change of back pressure is about 20 kPa in the developed S-P Converter. Absolutely speaking, the change of 20kPa is small, but it is big enough to drive a pilot valve to control an actuator.

**PILOT VALVE AND EXPERIMENTS**

The developed pilot valve is shown in figure 8. In figure 2, the sound is added to the S-P Converter directly in the air with the sound source placed very close to the head. But in the proposed SODC-Valve, it is required that the sound is conveyed by the supply tube. That means the head in figure 2 must be inserted inside the supply tube. It is clear that the S-P Converter in figure 2 can not be applied directly to a SODC-Valve. This problem is solved by introducing another vibration head. As shown in figure 8(a), the leaf spring stretches to both side of the fixing part with two heads attached at the end to compose two vibration elements. One is called resonance vibration element and the other is called flapped vibration element. Their heads are called resonance head and flapper head. The flapper vibration element is at atmosphere while the resonance vibration element is inserted in the supply tube filled with the sound. The resonance vibration element is adjusted with the vibration direction being along with the sound propagation direction to realize a large resonance vibration amplitude. The resonance vibration of the resonance vibration element is propagated through the leaf spring to the flapper vibration element. The resonance frequencies of the resonance vibration element and flapper vibration element are adjusted to be the same. From figure 8(b), the developed pilot has two parts. The upper part is consisted of flapper vibration element and nozzle, while the lower part is consisted of the resonance vibration element which is inserted into the supply tube with joint.
The step response of the pilot valve is investigated. From figure 11(a), the time lag of the back pressure is about 200ms, which means the interval from the time sound is added to the time when the back pressure rises to 50% of its maximum value. On the other hand, from figure 11(b), the time lag of the back pressure is 220ms, which means the interval from the time sound is stopped to the time when the back pressure falls to 50% of its maximum value. Two time lags are almost the same.

**MAIN VALVE**

The pilot pressure is about 20kPa and very small compared with supply pressure. A main valve is developed which can be driven by the 20kPa pilot pressure change. For convenience, a three port main valve is developed in this paper instead of a two port main valve. The schematic of main valve is shown in figure 12 and cross-sectional view is shown in figure 13. The diaphragm is fixed to the poppet so that the pilot pressure can drive the poppet directly. The spring force of the diaphragm is very small and can be neglected. The forces acts on the main valve can be described as the force of pilot pressure, spring force and force of supply pressure. When the pilot valve is OFF, the pilot pressure jumps up to its maximum and the sum of the spring force and the force of pilot pressure becomes bigger than the force of supply pressure. Resultantly, supply pressure port P is closed and port A is opened to the air through port R. When the pilot valve is ON, the pilot pressure falls down to its minimum and the force of supply pressure becomes bigger than the sum of the spring force and the force of pilot pressure. Resultantly, supply pressure port P is opened to port A and port R is closed. The main valve can be controlled by the pilot pressure without any influence of supply pressure.

The room above the diaphragm is the pilot room while the room below the diaphragm is open to the air. The stroke of the main poppet is about 0.5mm. When the O ring attached to the main poppet is pushed down to the valve seat, port A is connected to port R. When the O ring is pushed up to the valve seat, port A is connected to port P.
**SODC VALVE**

The SODC valve is shown in figure 14 and is composed of the developed pilot valve and main valve. The goal of this study is to construct a pneumatic multi-degree wearable system. In this study, two SODC valves are developed. The picture of two SODC valves with resonance frequency of 96Hz and 98Hz are shown in figure 15. Using Dry Ice Power Cell as power supply, wearable actuators developed in previous study and two SODC valves, a novel pneumatic multi-degree wearable system is realized. As shown in figure 16, there is no cord connected to the valves. The actuators used are Tail-Wrist and Fit-band [2].

![Figure 14 SODC-Valve](image)

**Fig.14 SODC-Valve**

![Fig.15 Photo of assembled SODC-Valves](image)

**Fig.15 Photo of assembled SODC-Valves**

![Fig.16 Wearable system driven by SODC-Valves with Dry-ice Power cell](image)

**Fig.16 Wearable system driven by SODC-Valves with Dry-ice Power cell**

In figure 17, the SODC valve with 96 Hz resonance frequency opens from 4s-6s, while the SODC valve with 98 Hz resonance frequency opens from 2s-8s. The two SODC valves can be controlled by sound simultaneously to drive two actuators.

**CONCLUSIONS**

In this paper, a sound operated directional control valve (SODC-Valve) is proposed which opens and closes in response to the sound of a specific frequency propagated inside the gas supply tube and therefore needs no electric wiring to convey the control signals. By using multi-frequency sound, several valves can be controlled simultaneously and resultantly the pneumatic multi-degree wearable system can be constructed compactly. Experimental results verify that the sound operated directional control valves are feasible and practical in pneumatic multi-degree-of-freedom wearable power assist system.

**REFERENCES**