2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Precise Bending Angle Control of Hydraulic Active Catheter by Pressure Pulse Drive

Koji Ikuta, Yoshikatsu Matsuda, Daisuke Yajima, Yusuke Ota
Department of Micro-Nano Systems Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
ikuta@mech.nagoya-u.ac.jp

Abstract: We aimed to develop an active catheter that could be used safely in human blood vessels. We proposed and developed a micro valve for a water pressure-driven system with multi-degrees of freedom, to produce an active catheter that is compact and not driven electrically. In this paper, we proposed a new method that uses pressure pulses to control the bending angle of the active segment. We experimentally verified this control method using the new valve design.

I. INTRODUCTION

Catheterization is a typical medical technique that is popular in non-invasive or minimally invasive surgery. A catheter is a thin tube that can be inserted into a body cavity or vessel to allow examination or treatment. Until now, catheters have been inserted into blood vessels using a guide wire. This procedure is difficult because of the restricted inner diameter of vessels and the way in which they bend, twist or branch into complex networks.

Active catheters are seen as the solution to this problem as they can potentially bend and twist their axes in any direction and choose a direction at a branch point of a vessel. Studies have been carried out to develop an active catheter of this kind,[1-3] but a safe and practical instrument has yet to be achieved. In these conventional studies, electric actuators were attached to the parts inserted into the body. However, they have the possibility of injuring the patient due to their physical construction. In addition, poor durability due to their complex internal mechanism and bulkiness due to the additional driving lines needed for additional joints, prevent successful practical application.

Our solution is a hydraulic active catheter with multiple segments and a unique drive system capable of bending two or more segments of the catheter using only hydraulic pressure. This system has the advantage of not using electrical power in any part to be inserted into the body so the problems of electrical leakage or heat generation will not occur. It is also practical to use as segments can be added without the need for additional driving lines.[4-6]

II. HYDRAULIC ACTIVE CATHETER

A. Basic Concept

Figure 1 shows the concept of the hydraulic active catheter proposed in this study. These active segments have a bellows shaped bending actuator and a micro valve to control the opening and closing of a channel. This valve has its own specific pressure range, called the driving pressure range, for opening its channel. These active segments are connected to a single control tube in series, and driven in response to the pressure in the control tube. Conventional saline is used as the driving fluid so that the patient would not be exposed to any danger in the event of a leak.

B. Single-input, Multi-output System

In our device, we use a Band Pass Valve (BPV) that we

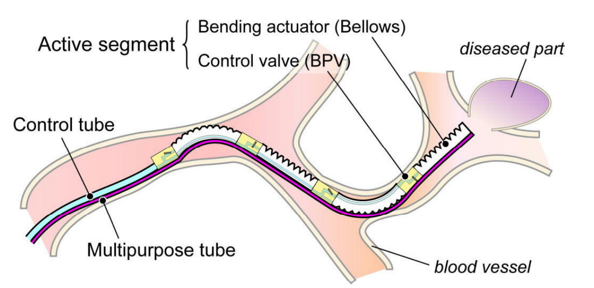


Fig.1 Basic concept of hydraulic active catheter

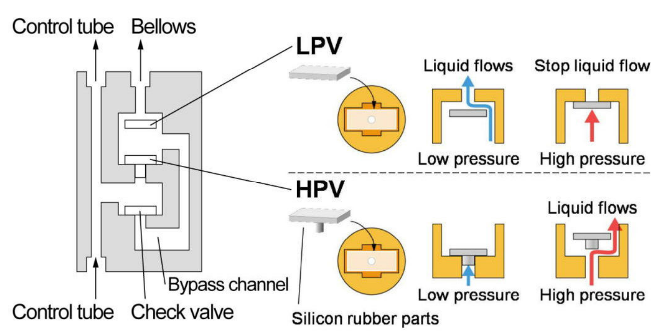


Fig.2 Composition of BPV

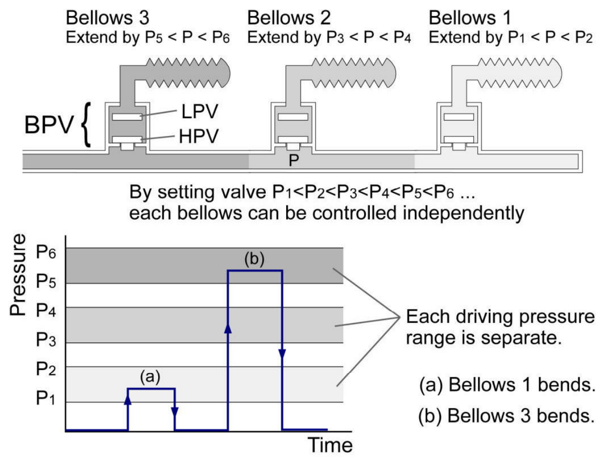


Fig.3 The "Single-input, multi-output" control mechanism

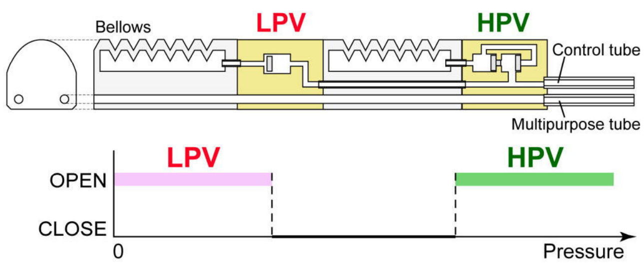


Fig.4 Simplified composition with two active segments

originally developed. The BPV has a Low Pass Valve (LPV) for closing its channel and a High Pass Valve (HPV) for opening its channel in response to applied pressure, and a check valve to return the supplied fluid (Figure 2). The range within which both the LPV and the HPV open is called the driving pressure range, and the BPV only opens its channel within this pressure range, to supply the fluid to the bellows actuator.

Each active segment has its own BPV with its own driving pressure range that does not overlap with other active segments pressure ranges (Figure 3). We can control these segments independently, by controlling the magnitude of hydraulic pressure. This is the feature of the device that allows the single-input multi-output system to be constituted easily.

C. The Simplified Model with Two Segments for Clinical Use

We developed a simplified composition model with two segments for clinical use. In this model, we designed a separated driving pressure range for each segment, using the LPV and the HPV respectively. As shown in Figure 4, the LPV is used at the tip segment and the HPV is used at the base segment. We can independently control the two active segments of the device by using the low-pressure and high-pressure input ranges appropriately. We applied a hybrid micro stereolithography, proposed and developed in our laboratory, to make these valves.[7]

This model has only half parts of the valving elements compared with the first concept model. So it is easy to design and fabricate a smaller model, and durable for long operation. In addition, this model has two multipurpose channels for dye injection and so on. Each diameter is 0.5 [mm]. They are fabricated by silicon rubber molding in each bellows and micro stereolithography in each valve.

III. PROPOSITION OF PRESSURE PULSE DRIVE

A. The Issue of the Bending Angle Control by Pressure

There are two major issues concerning the bending angle control of the two active segments. 1) It was difficult to control the bending angle of the base segment; and 2) it was impossible to control two segments simultaneously because of the principle originally used.

Figure 4 shows the components of the control device. In this system, we use a syringe to supply the fluid, and measure the difference between the pressure and the command value for feedback control. We apply a suitable pressure command for each driving pressure range to bend each active segment. This system has a semi-closed feedback loop and since the bending angle is not sensed, it is necessary to examine the bending characteristics of each active segment beforehand.

In the simplified model mentioned above, the bending angle of the tip segment with LPV, which is normally opened, is set to correspond to the magnitude of pressure such that the higher the pressure, the higher the bending

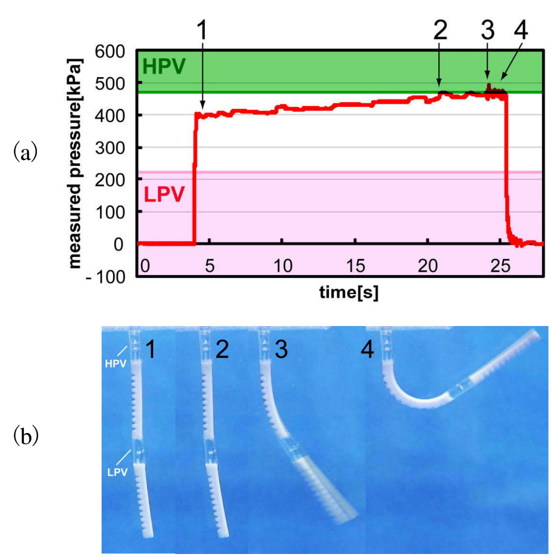


Fig.5 Base segment bending by previous control method
(a)Time profile (b)Actual motion

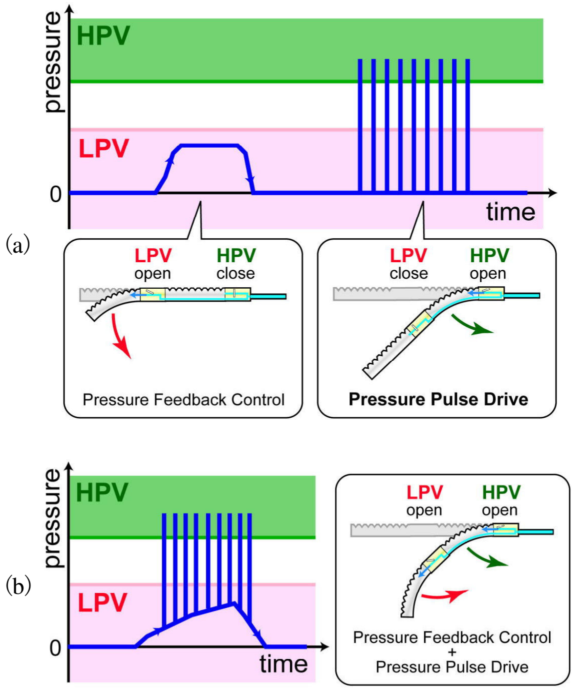


Fig.6 New control method using pulse wave
(a)Precise control of base segment
(b)Simultaneous bending of both segments

angle will be. Therefore, if the bending characteristics are known, it is possible to control the bending angle precisely using pressure control.

On the other hand, the base segment with the HPV, which is normally closed, bends only after the input pressure becomes more than the HPV's release pressure. As such, it is necessary to control the duration of pressure input for precise bending of the active segment. However, since the HPV's release pressure is more than about 450 kPa, the difference in the bellows is large when the HPV is opened, and flow rate to the base segment is also large. This results in the sudden bending of the base segment and makes the bending angle difficult to control. Figure 5 shows the appearance of the base segment's bending when the HPV is actually opened by the pressure control. It is shown that the bending angle of the segment changed rapidly near 25 s that the HPV seems to have opened. Such rapid bending motion is undesirable during operation, because it is only possible to check the bending angle of the segment by X ray imaging.

Moreover, since this pressure control method can pressurize only one segment, theoretically, it is impossible to control two segments simultaneously. It is possible to control the orientation of the two bending segments finally by alternating input pressure to each segment. In order to insert the active catheter into the body more smoothly, the simultaneous and non-interfering bending motion of these segments are required.

B. Proposition of the Pressure Pulse Drive

To solve the problems mentioned above, we proposed a new control method that exerts the pressure in pulses. We call it pressure pulse drive. Figure 6 shows a schematic view of the pressure wave and the actual bending motion of the hydraulic active catheter.

In this method, we use a pulse wave to open the HPV. We can open the HPV for a short time without controlling the duration of pressure input. The bending angle of the base segment increases as the number of input pulses increase (Figure 6 (a)).

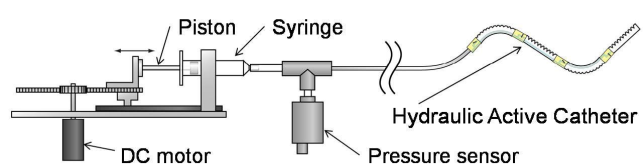
Moreover, this pulse wave is generated by temporarily stopping the pressure feedback by making the syringe momentarily go back and forth. Therefore, it is possible to bend two segments simultaneously by the merging the pressure control to drive the tip segment with the pulse drive (Figure 6 (b)).

IV. OPTIMIZED DESIGN OF DRIVING PRESSURE RANGE

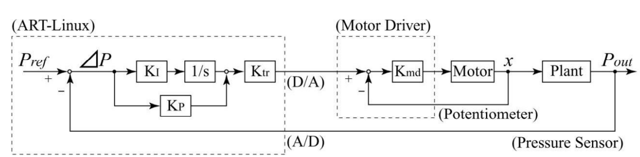
A. Specification for the Pulse Drive

The pressure pulse drive requires a design in which the bending angle of the tip segment responds only to pressure and the one of the base segment responds only to the input pulse number. The specifications for the valve designs necessary to achieve those features are as follows.

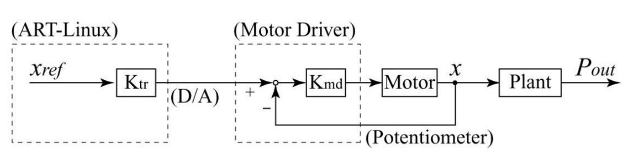
Figure 7 shows the schematic of the pressure control device and the block diagram for pressure and position



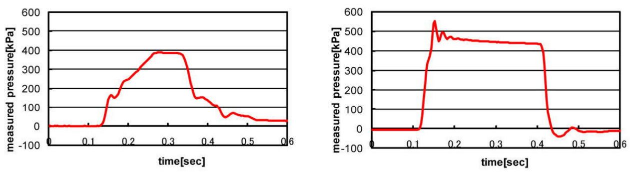
(a)Pressure control device



(b)Block diagram of pressure control



(c)Block diagram of position control
Fig.7 Control system for hydraulic active catheter



(a)Pressure control (b)Position control

Fig.8 Shape of pressure pulse

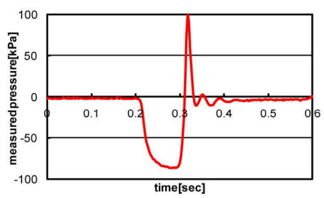


Fig.9 Negative pressure pulse

feedback control respectively. Figure 8 shows the input pulse shape for using each control. The rectangular pulse by pressure control has a late response, while the one by position control has a response fast enough for the pressure pulse drive. However, there is a negative overshoot after inputting the pulse for position control, and each segment has a negative pressure input. This causes undesirable motion of the tip segment. On the other hand, the base segment has no ability to increase its bending angle with an increase in the number of input pulses. This is because the release pressure of the check valve is too low to retain the supplied fluid after the pulse has been input. Therefore, the base segment requires the ability to maintain its bending angle after the pulse has been input and also to straighten its body through negative pressure pulsing as shown in Figure 9.

The driving pressure ranges of the previous LPV and the HPV do not overlap in the positive pressure range, but overlap in the negative pressure range (Figure 10(a)). In order to make the pressure pulse drive practical, it is necessary to design the device so that the driving pressure ranges do not overlap in either the positive or the negative pressure ranges (Figure 10(b)).

B. Optimized Design of the LPV

The previous LPV has a design that provides only for the upper bound of the driving pressure range, and it is normally open in the negative pressure range. It is influenced by the negative overshoot of the pulse and the negative pressure pulse, and too much fluid is returned from the bellows actuator. This characteristic is not desirable for practical operation.

Therefore, we changed the LPV design to create a lower bound to the driving pressure range. As shown in Figure 11, we changed the channel on the entrance side of the LPV to close its channel whenever the high frequency pulses were input, regardless of whether these pulses were exerting positive or negative pressure.

C. Optimized Design of the HPV

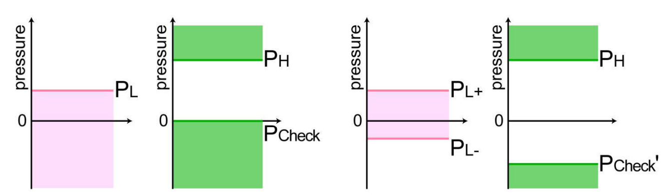
The HPV is a one-way valve, so it needs the check valve opened in the opposite direction to return the supplied fluid. They are used in the base segment together. The check valve of the previous base segment has a release pressure but it is almost equal to zero, so it returns the supplied fluid immediately the pressure in the driving tube is lower than the pressure in the bellows. Therefore there is the problem that the base segment is not able to retain the supplied fluid and to straighten its body in response to the falling of the pulse.

Therefore, we changed the design of such check valves as the HPV to increase the release pressure as shown in Figure 11. As a result, it became possible to maintain the degree of bending even if the pressure in the bellows became high. Moreover, we could straighten the base segment's body by inputting negative pressure pulses and opening the check valve. It also made it possible to change the bending angle by increasing the number of positive or negative pulse inputs.

V. EXPERIMENTAL VERIFICATION

A. Verification Testing of the Bending Angle Control by the Pressure Pulse Drive

We constructed the active catheter with the above-mentioned design and verified the pressure pulse drive.



(a)Previous model (b)After modification

Fig.10 Driving pressure range of the LPV and the HPV

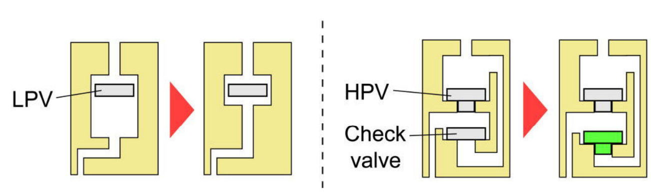


Fig.11 Redesigns of LPV and HPV for pressure pulse drive

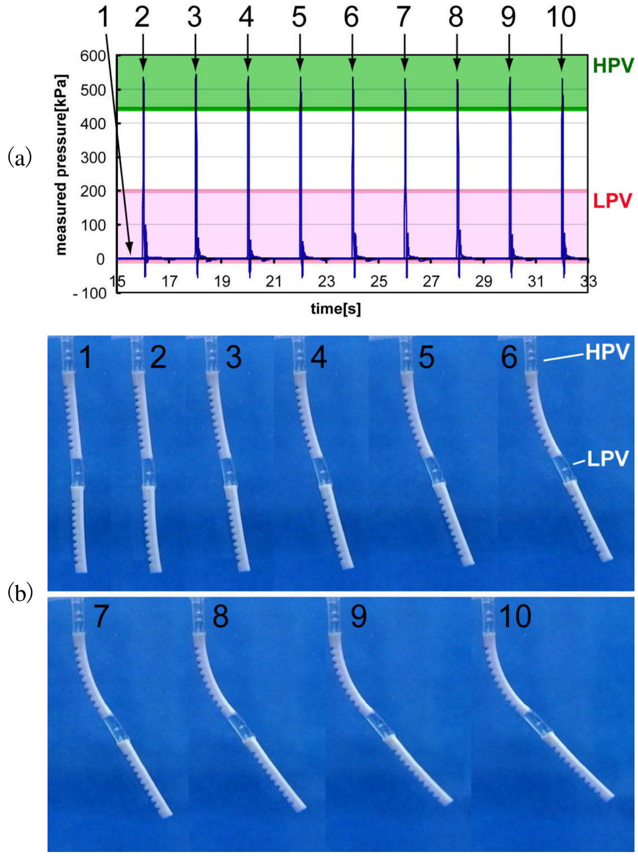


Fig.12 Base segment bending by pulse wave
(a)Time profile (b)Actual motion

First, we tested the motion of the base segment in response to the pulse input. Figure 12 shows the bending motion of the base segment when the pulse wave is applied. Figure 12(b) shows that only the base segment has bent in response to the pulse input, and that the new valve has performed well. It also allowed a more precise control of the bending angle compared with the previous method.

Next, we tested the bending characteristics in response to the change in the input pulse shape. Figure 13 shows the way to measure the bending angle of the base segment. These images are captured from the video picture of the examination. Figure 14 and Figure 15 show the input pulse shape and the relation between the bending angle and the input pulse number. The bending angle for each pulse increases if the width and the magnitude of the pulse are enlarged. This allows a rapid bending motion. On the other hand, the bending angle for each pulse decreases if the width and the magnitude of the pulse are reduced. This allows a highly accurate bending motion. This demonstrated the ability of the device to achieve rapid and highly accurate maneuverability, and suggests there is the possibility that operation time can be shortened thanks to this characteristic.

Figures 14 and 15 show that the gradient of the bending characteristic decreases with pulse input number. This is because the pressure in the bellows makes the release pressure of the HPV increase, and this causes a decrease of the flow rate into the bellows. It is necessary to correct the magnitude of the input pulse according to these characteristics to control the bending angle more precisely.

B. Verification Testing of the Simultaneous Drive of Two Segments

Finally, we verified the simultaneous non-interfering drive of two segments by time-sharing with the pressure control and pulse input. Figure 16 shows the pressure wave and actual bending motion.

Figure 16A shows the simultaneous drive of two segments by time-sharing with the pressure control and pulse input. Figure 16B shows the bending of the tip segment using the low-pressure control, while maintaining the orientation of the base segment. Figure 16C shows the straightening of the base segment using negative pressure pulsing, while maintaining the orientation of the tip segment.

When a pulse is input, a positive and negative overshoot

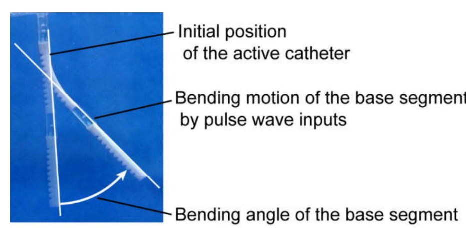


Fig.13 Measurement of the base segment's bending angle

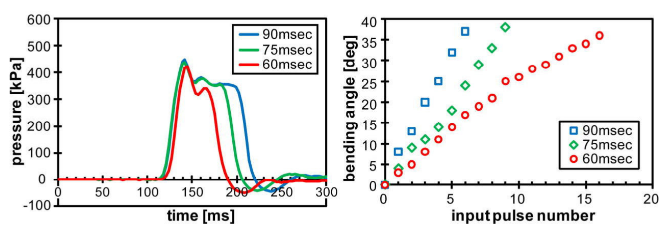


Fig.14 Comparison of bending characteristics by pulse width

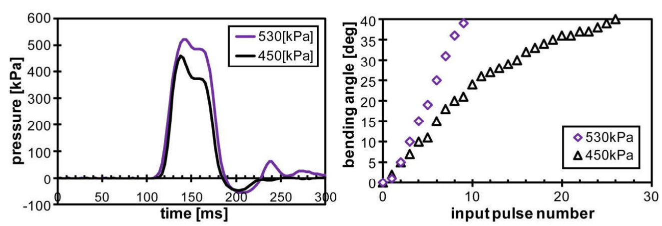


Fig.15 Comparison of bending characteristics by pulse amplitude

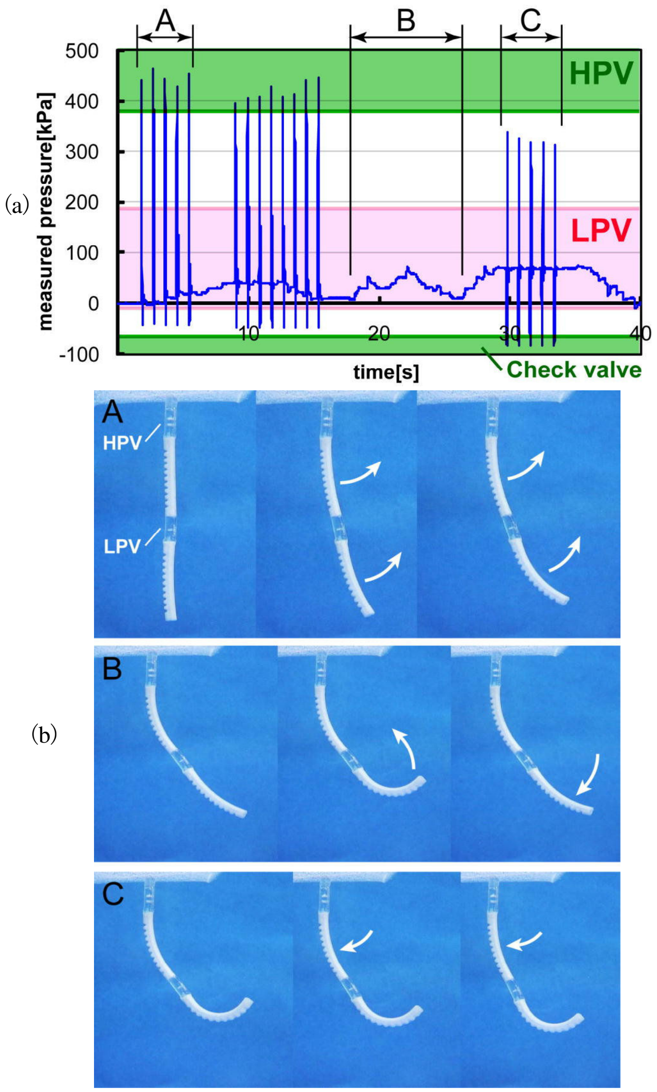


Fig.16 Two segments bending by pulse wave and pressure control (a)Time profile (b)Actual motion

A: Simultaneous bending of two segments

B: Tip segment bending, while base segment position is held

C: Tip segment position is held, while base segment is extended

occurs. Especially, when the negative pressure pulse is input, a prominent positive undershoot occurs. In this test, since the overshoot and undershoot didn't reach the driving pressure ranges of the HPV or the check valve, it didn't cause interference between the two segments. Even if the overshoot were to reach those driving pressure ranges, we believe that it wouldn't become a problem in practical use because the overshoot pressure waves last a shorter time (about 0.01s) than the input pulse (about 0.1s).

These results demonstrate the achievement of a simultaneous non-interfering drive of two segments by the pressure pulse drive.

VI. CONCLUSION

In this paper, we proposed a new control method for the hydraulic active catheter. We recognized the difficulty in controlling the bending angle using pressure control, and proposed a pressure pulse drive to solve this problem. We subdivided the flow rate of the HPV by inputting the pressure pulse, and achieved precise control of the bending angle in the high-pressure range. Moreover, we achieved the simultaneous drive of two active segments by merging the pulse input with the pressure control.

We used an optimized two-segment model for these experiments. However, we are convinced that bending angle control using the pressure pulse drive is applicable for use with a greater number of active segments, with different driving pressure ranges. In the future, we aim to develop an active catheter with more degrees of freedom and to prepare it for clinical testing.

REFERENCES

[1] S.Guo, T.Fukuda, F.Arai, M.Negoro, K.Oguro, "A Study on Active Catheter System Structure Experimental Results and Characteristic Evaluation of Active Catheter with Multi DOF", Journal of the Robotics Society of Japan, Vol.14 No.6, pp.820-835, 1996.

[2] M.Tanimoto et al, "Improvement of Safety in Telemedicine System", Proceedings of 3rd Robotics Symposia, pp.139-144, 1998.

[3] Y.Haga, M.Esashi, "Small Diameter Active Catheter Using Shape Memory Alloy Coils", The transactions of the Institute of Electrical Engineers of Japan, Vol.120 No.11, pp.509-514, 2000.

[4] K.Ikuta, H.Ichikawa and K.Suzuki, "Safety-active Catheter with Multiple-segments Driven by Micro Hydraulic Actuators", Proc. of Medical Image Computing and Computer-Assisted Intervention (MICCAI2002), pp.182-191, 2002.

[5] K.Ikuta, H.Ichikawa, K.Suzuki and T.Yamamoto, "Safety Active Catheter with Multi-Segments Driven by Innovative Hydro-Pressure Micro Actuators", Proceedings of the IEEE International Workshop on Micro Electro Mechanical Systems (MEMS2003), pp.130-135, 2003.

[6] K.Ikuta, H.Ichikawa, K.Suzuki and D.Yajima, "Multi-degree of Freedom Hydraulic Pressure Driven Safety Active Catheter", Proceedings of the 2006 IEEE International Conference on Robotics and Automation Conference, pp.4161-4166, 2006.

[7] K.Ikuta, S.Maruo, T.Fujisawa and A.Yamada, "Micro Concentrator with Opto-sense Micro Reactor for Biochemical IC Chip Family - 3D Composite Structure and Experimental Verification - ", Proceedings of the IEEE International Workshop on Micro Electro Mechanical Systems (MEMS99), pp.376-381, 1999.