DEVELOPMENT OF DIGITAL TYPE TAP-WATER DRIVE FLOW CONTROL VALVE

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ABSTRACT

This study concerned with development of digital type tap-water drive flow control valve for water hydraulic systems. In this study we developed a novel type of valve which can generate 10 steps of output flow rate. In addition, a back pressure supply mechanism is applied to the developed valve to assist torque of a stepping motor driving a rotary disk in the valve. The improved valve with the back pressure supply mechanism is compared with conventional digital valve units using typical On/Off valves. As a result, it was confirmed that the size was reduced by 30% and the mass was reduced by 70%.

Keywords: Water hydaurlics, Digital fluid power, Digital valve unit, Flow control valve

1. INTRODUCTION

Water hydraulic systems have been applied to food processing, medical instrument, and semiconductor devices, which require high cleanliness and environmental friendliness shown in **Figure 1** [1]. This is because their working fluid is water and the systems have 100% oil-free characteristics. In particular, tap-water drive systems take much more attention because they need no hydraulic pumps. The systems are likely to be used at home because supply and disposal of water as a working fluid is easy. In addition, there is no danger which generates heat and an electric shock. From these reasons, tap-water drive systems can be a new driving power source.

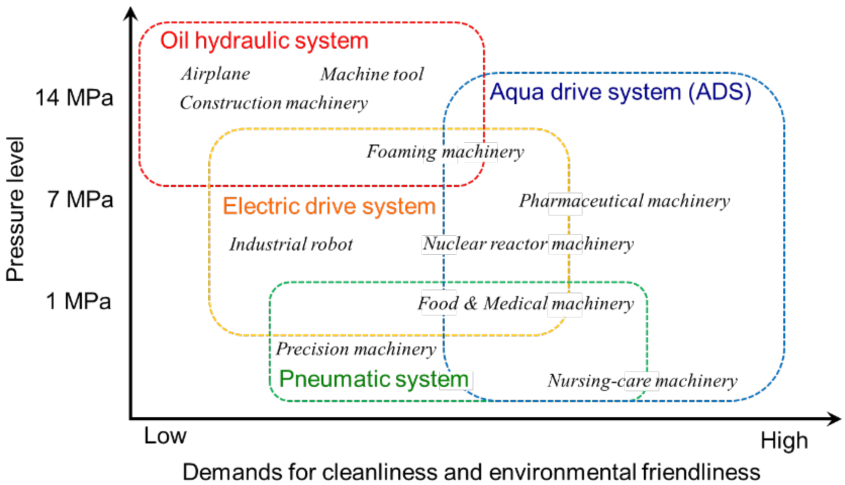
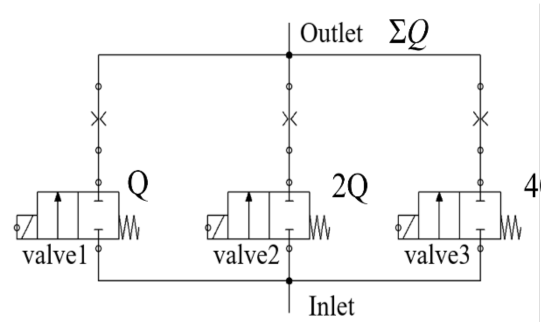


Figure 1: comparison of four driving systems

On the other hand, the systems have following problems; 1) Maximum supply pressure of tap-water in Japan is only 300kPa, 2) Leakage of the systems is relatively large due to low viscosity of water, 3) Few types of water hydraulic elemental equipment have been developed compared to the other driving systems such as oil hydraulic and pneumatic systems. This study focuses on third problem and aims to develop a new component for tap-water drive systems.
In general, there are two type valves for hydraulic systems to control pressure or flow rate. One is On/Off valves and they have characteristics that their operations are only open or close. Although the valves are also low priced, they can only switch the direction of flow but cannot control pressure or flow rate directly. The other is proportional valves for hydraulic systems and they have characteristics that can control valve opening area continuously, which means they can control pressure or flow rate. The valves, however, are high priced among other drive sources. From these problems, when high control performance is required, we have to apply proportional valves.
Recently, digital fluid power has been focused and researched actively [1]-[3]. As related study for oil hydraulic systems, digital valve unit (DVU, for short) was proposed in Europe. DVU can regulate flow rate in incremental steps by using of pulse code modulation (PCM) method [4]. PCM is known as a way of analog-digital conversion and the way has been widely used for compact disks. **Figure 2** shows structure of DVU and obtained outlet flow rate by combination of the valve On/Off patterns. DVU consists of a number of typical On/Off valves and can generate stepwise flow rate by changing combination of On/Off pattern for each valves. For instance, when rated flow rate of three valves are set to Q, $2Q$, and $4Q$, outlet flow rate of DVU can be from 0 to $7Q$, which is like binary codes. Thus, DVU are less costly than proportional valves because it uses only On/Off valves and the valves in general can be gotten inexpensively. However, whole system of DVU may be large size and expensive when the system consists of lots of valves, which means it requires precise incremental steps of outlet flow, in order to make its control performance high. In related study, DVU showed possibility of reduction in energy consumption compared with the energy consumption of a typical 2/2 proportional valve. In addition, it is clear that the concept difficulties are valve states uncertainty and pressure peaks.



0 : closed valve 1 : open valve			Outlet Flow
V3(4Q)	V2(2Q)	V1(1Q)	(ΣQ)
0	0	0	0
0	0	1	1
0	1	0	2
0	1	1	3
1	0	0	4
1	0	1	5
1	1	0	6
1	1	1	7

1: On
0: Off
V: valve
ΣQ: outlet flow

Figure 2: Structure of digital valve unit and obtained outlet flow of DVU

2. DIGITAL TYPE FLOW CONTROL VALVE

The aim of this study is development of the digital flow control valve with incremental steps of outlet flow for tap-water drive systems. In particular, to realize the function of DVU with a valve can solve one of above problems for DVU. Also, it is expected that the developed valve can reduce its weight and package size of a whole system. Thus, the valve can provide a new choice of valves for water hydraulic systems.
Figure 3 shows structure and combination of On/Off pattern of a developed valve which we call it digital type flow control valve in this study. The valve consists of a stepping motor, some steel balls, a rotary disk, input and output ports. The output port has a number of orifices corresponding to a

number of On/Off valves in DVU. The steel balls in the rotary disk closed these orifices when the balls overlapped on the orifices. Position arrangement of the balls is set on every 30 degrees on the rotary disk shown in **Figure 3**. Then, the valve can generate incremental steps of outlet flow rate by rotation of the stepping motor. For instance, position 1 which consists of one opening and five closing orifices indicates outlet flow rate of Q and position 2 which consists of two opening and four closing orifices indicates outlet flow rate of $2Q$ and position 3 which consists of three opening and three closing orifices indicates outlet flow rate of $3Q$. Thus, position arrangement of the steel balls with one rotary disk can achieves stepwise outlet flow by using a stepping motor. Note that we can get more steps of flow rate when the rotary disk has different orifice sizes such as A, $2A$, $4A$ and more although this describes only six steps of outlet flow rate which is from Q to $6Q$. Moreover, If the orifice diameter on the rotary disk is equivalent to it on typical On/Off valves consisting conventional DVU, package size and total cost of a whole system can be drastically reduced.

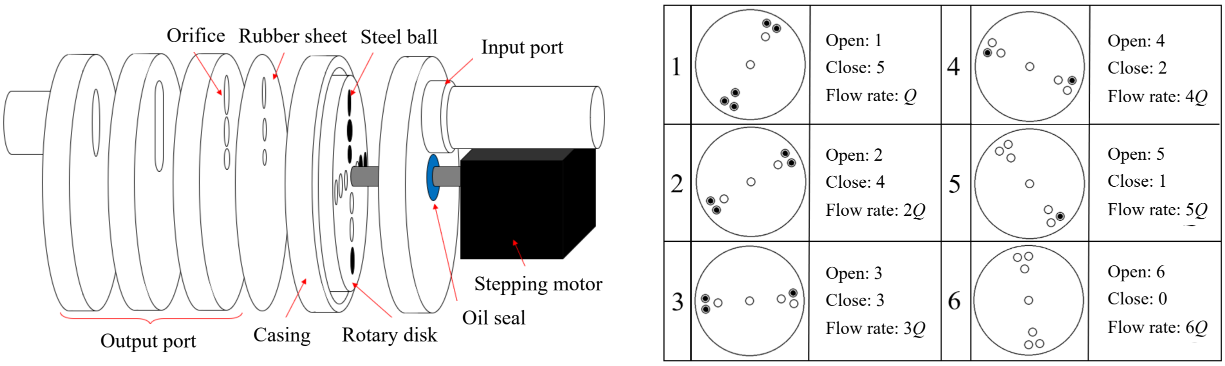


Figure 3: Structure and combination of On/Off pattern for digital type flow control valve

Figure 4 shows a prototype of digital type On/Off valve. The developed valve consists of a stepping motor (ST-42BYG020, Mercury Motor), an acrylic rotary disk with 36 orifices (diameter of 1.8 mm) shown in **Figure 3**, acrylic plates with input and output ports, an oil seal, a rubber sheet (thickness of 0.5 mm) with 6 holes (diameter of 1.4 mm), 15 steel balls (diameter of 3 mm), and input and output connectors. The valve can theoretically generate 7 steps of output flow rate including fully closed. **Figure 5** shows an experimental setup for flow measurement of the developed valve. The setup consists of the valve, a pressure sensor (PSE560-02, SMC Corp.), a flowmeter (FD-XS20, KEYENCE Corp.), and a micro-computer (H8/3664F, Renesas Electronics Corp.) to drive the stepping motor on the valve. Flow measurement is carried out under various supply pressure conditions from 0.05 to 0.30 MPa, which assumes tap-water pressure level and no-load. **Figure 6** shows experimental result for flow measurement of the valve. As seen in the result, the valve can generate incremental steps of output flow regardless of supply pressure and the output flow seems to be proportional to the number of opening orifices on the rotary disk.

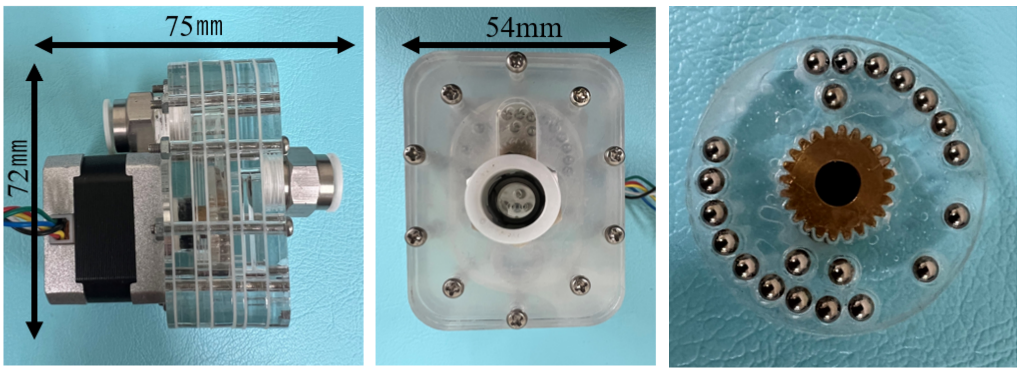


Figure 4: Prototype of digital type flow control valve

The developed valve, however, has a problem that the torque of the stepping motor may be insufficient when number of orifices and steel balls have to be increased in order to increase steps of output flow rate of the valve. To overcome this difficulty, we propose an assist mechanism using back pressure of the valve to rotate the stepping motor.

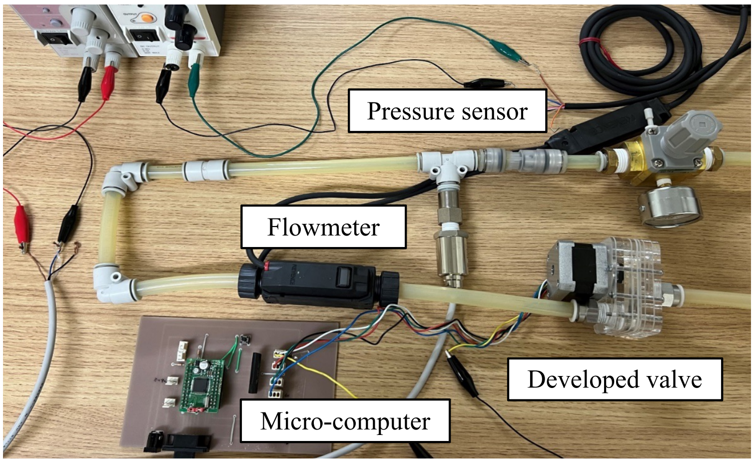


Figure 5: Experimental setup for flow measurement of developed valve

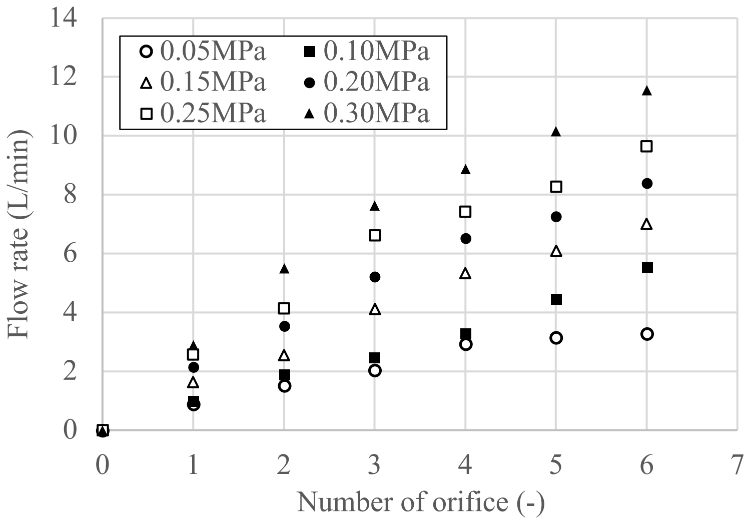


Figure 6: Experimental result (flow measurement of developed valve)

3. IMPROVEMENT OF DIGITAL TYPE FLOW CONTROL VALVE

Improvement of the developed valve is considered as mentioned above. A key concept of improvement is to use back pressure of the valve for torque assist of motor rotation. **Figure 7** describes a schematic diagram of a back pressure supply mechanism of the improved valve. The symbols of the ball valves in the figure express the orifices in the rotary disk of the valve and there exists an additional On/Off valve connecting input and output ports of the flow control valve directly. When the stepping motor connected with the rotary disk rotates, the On/Off valve opens and then back pressure can be generated to balance supply and back pressure around the steel ball. On the other hand, this study aims to reduce weight and package size of the proposed valve and it also needs an additional small-sized bypass valve in the back pressure supply mechanism.

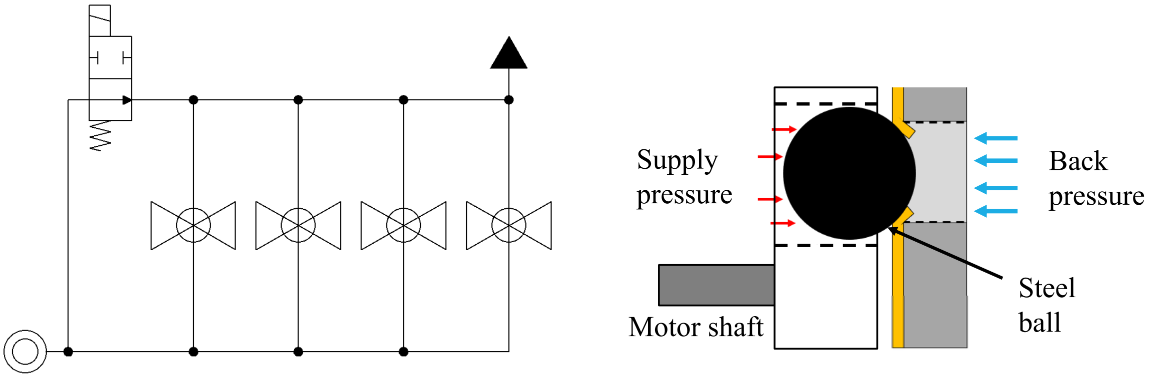


Figure 7: Schematic diagram of back pressure supply mechanism

3.1. Back pressure supply valve

Back pressure supply mechanism should have small-sized and simple structure. In this study, we apply a magnetic holding mechanism to open/close motions of an orifice. **Figure 8** shows a schematic diagram of a back pressure supply valve using magnet balls and coil to move a magnet ball. Exciting the coil momentarily, magnet ball for orifice is moved and overlapped on the orifice, that is, the valve can be closed. Same way for excitation of the coil can open the valve because the magnet ball can rotate and the other magnet ball on the opposite side can pull the ball for orifice.

Figure 9 shows a prototype of back pressure supply valve. The valve consists of three magnet balls (diameter of 3 mm), an enamel wire coil (diameter of 0.2 mm and the number of turns of 200 times), a rubber sheet (thickness of 0.5 mm), casing with input and output ports made by 3D printer, input and output connectors. It has an orifice of 1.8 mm inside and has also relatively small-sized and simple structure.

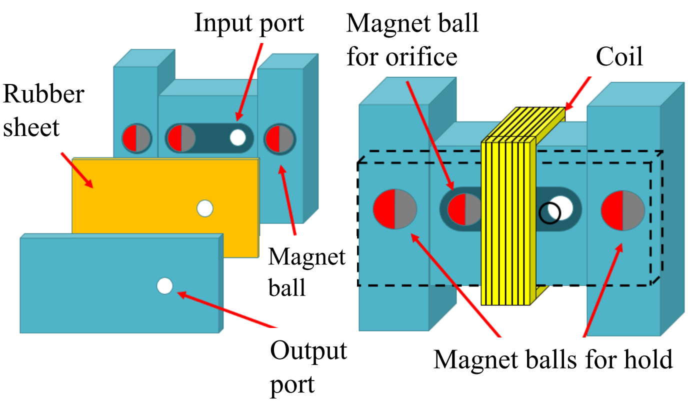


Figure 8: Schematic diagram of back pressure supply valve

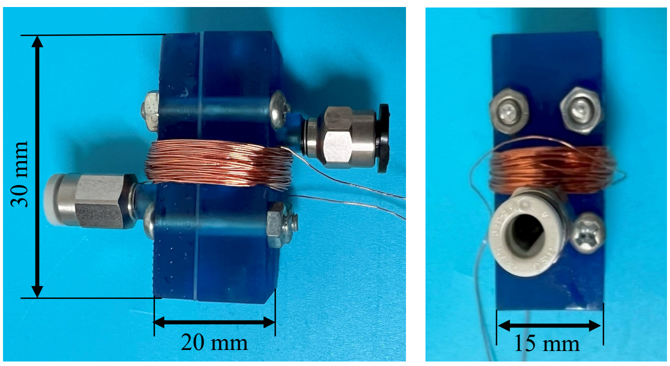


Figure 9: Prototype of back pressure supply valve

3.2. Improved flow control valve with back pressure supply mechanism

The previous developed valve with six steps of output flow has the problem of motor torque and we apply the back pressure supply mechanism mentioned above to overcome the difficulty. Improved flow control valve with the mechanism is tested here. The improved valve has 10 steps of output flow as shown in **Figure 10**. The combination of On/Off pattern for the valve is basically same as the combination for the previous valve in **Figure 3**. A prototype of the improved valve, which is in **Figure 11** has length of 70 mm, width of 70 mm, height of 60 mm and its mass is approximately 400 g. **Figure 11** shows an experimental setup for flow measurement of the improved valve with the back pressure supply valve. The setup consists of the improved valve, a couple of pressure sensors (PSE560-02, SMC Corp.), a flowmeter (FD-XS20, KEYENCE Corp.), and a micro-computer (ESP32-WROOM-32) to drive the stepping motor on the valve. Flow measurement is carried out under various supply pressure conditions from 0.05 to 0.30 MPa, which is same conditions as previous flow measurement in Chap. 2. **Figure 12** shows experimental result for flow measurement of the improved valve. As seen in the result, the improved valve can generate more incremental steps of output flow regardless of supply pressure than the steps of the previous valve which has up to six steps due to shortage of torque of the stepping motor. Thereby, it is confirmed that the additional back pressure supply mechanism can work well. Note that the orifice size of the back pressure supply valve is same as the orifice in the improved valve and it means that the improved valve has totally 8 steps of output flow rate with additional one step.

Table 1 lists comparison of the digital type flow control valve develop in this study with DVU using typical On/Off valves. The On/Off valves used in DVU (USG-3-6-2, CKD Corp.) has same orifice diameter as the one of the developed valve. As a result, the size was reduced by 30% and the mass was reduced by 70%.

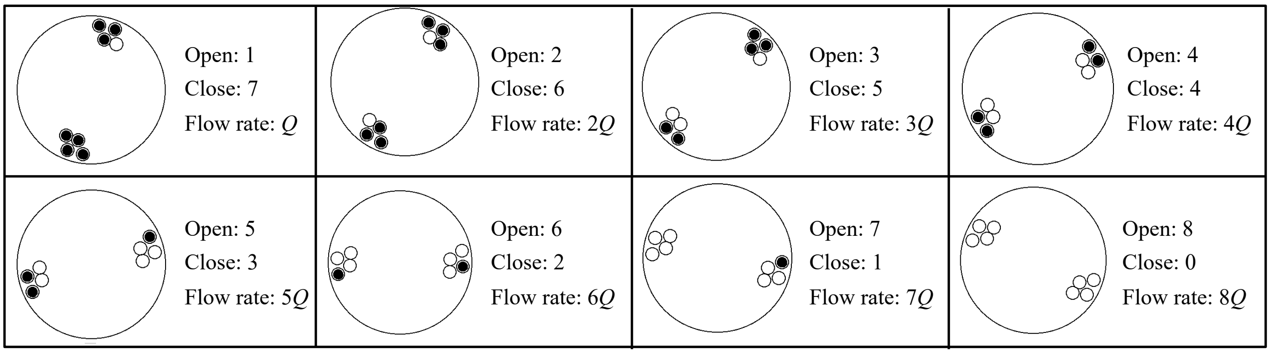


Figure 10: Combination of On/Off pattern for improved valve

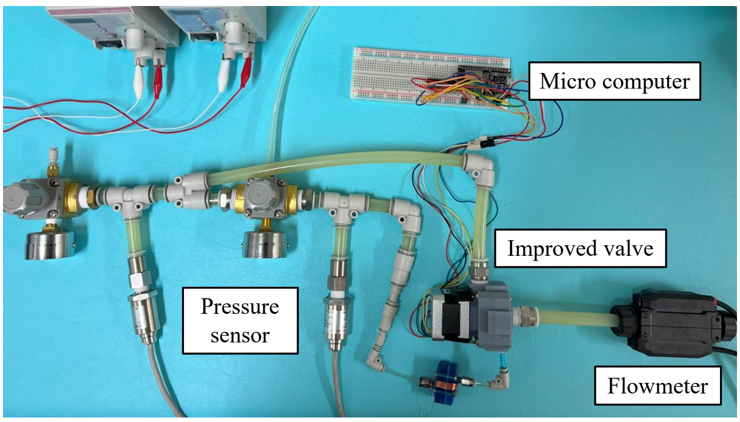


Figure 11: Experimental setup for flow measurement of improved valve

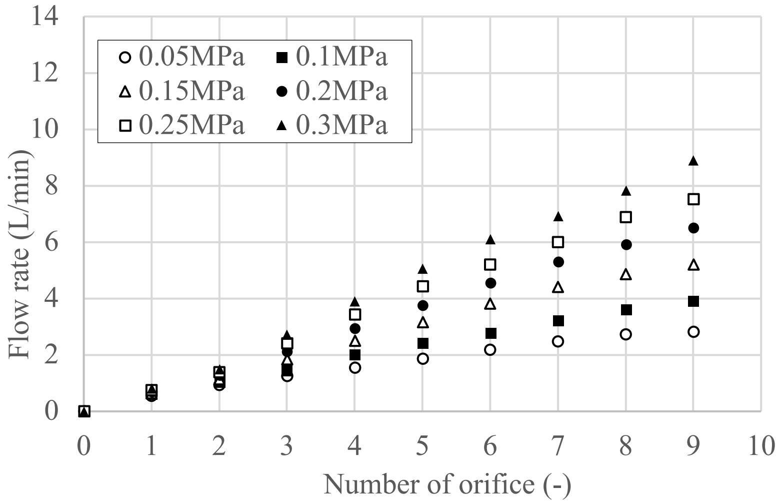


Figure 12: Experimental result (flow measurement of improved valve)

Table 1: Comparison of developed valve with DVU using typical On/Off valves

Comparative parameters	Developed valve	DVU using 9 On/Off valves
Size (L × W × H)	70 mm × 70 mm × 60 mm	80 mm × 75 mm × 75 mm
Total mass	400 g	1350 g
Orifice diameter	1.8 mm	1.8 mm

4. CONCLUSION

This study concerned with development of digital type tap-water drive flow control valve to give another choice of flow/direction control valves, which are generally On/Off valves and proportional/servo valves, for water hydraulic systems. In this study, we developed a novel type of valve which can generate 10 steps of output flow rate. In addition, a back pressure supply mechanism was applied to the developed valve to assist torque of the stepping motor driving a rotary disk in the valve. The improved valve with the back pressure supply mechanism was compared with DVU using typical On/Off valves. As a result, it was confirmed that the size was reduced by 30% and the mass was reduced by 70%. Thus, a compact, lightweight valve with 10 steps of output flow was realized.
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