Development of a Large Flow-rate High Speed On/Off Valve for Underwater Hydraulic Ejection System

Linyi Gu, Lin Li, Jiawang Chen, Qingmiao Zhang
The State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University
Hangzhou, China
lygu@zju.edu.cn/ sharin@zju.edu.cn/ arwang@zju.edu.cn

Xinran Wu
Hangzhou Universal Control Mechanical Electronic Engineering Ltd.
Hangzhou, China
jackie.w@163.com

Junyi Yang, Minhui Zheng
Second Institute of Oceanography,
State Oceanic Administration
Hangzhou, China
junyiyang@sio.org.cn / zhengmh@sio.org.cn

***Abstract*—For ROV carried Underwater Hydraulic Ejection Systems (UHES), the initial ejecting speed and ejecting distance depends on the response of its high speed on/off valves, together with its steady and transient flow rate. However, the flow rate capacity and response of general high speed valve are too small and too slow to meet the demand of most UHES. In this paper, a double spool type on/off valve is put forward to create a flowing-out type valve port, so that the steady flow force could be reduced to 1/3, and the direction of transient flow force could be changed to help the electromagnet opening or closing the valve port. After analyzing the steady and transient flow force of the double spool and flowing-out type valve port, its model is established, and the effects of flow force on this valve are compared with general poppet valves through Computational Fluid Dynamics (CFD) software. Simulation results show that, the valve's response could reach 2.25ms (on) and 2.15ms (off) at 48V power supply while the rated flow rate is 60L/min. Experimental results are also satisfactory.**

Keywords—High speed on/off valve; Double spool type valve; Flowing-out type valve port; Underwater hydraulic ejection system

I. INTRODUCTION

For ROV carried Underwater Hydraulic Ejection Systems (UHES) as shown in Fig.1, the initial ejecting speed and ejecting distance depends on the response of its high speed on/off valves, especially its steady and transient flow rate.

However, the flow rate capacity and response of general high speed valve are too small and too slow to meet the demand of most UHES. It may cause serious issues for ROV carried UHES. For, the ejected devices may be push back by current and hit ROV if the ejecting distance is not enough. Moreover, some ejected devices may entangle the ROV's thrusters and leads to serious damage.

In this paper, a double spool type on/off valve is put forward to create a outflow at its valve port, so that the steady flow force could be decreased, and the transient flow force could help the sleeve to open and close the valve port.

II. DESIGN OF THE DOUBLE SPOOL TYPE ON/OFF VALVE

A. Structure and principle

The structure of the double spool type on/off valve is shown in Fig.2. Instead of the traditional solid core valve spool, this valve spool are separated into two parts: a very thin moving sleeve and a fixed spool center.

The main purpose of this double spool type on/off valve is not only to reduce the weight of moving part simply, but also to reduce the area of moving part, and to change its flow-rate's direction. There are 2 valve ports: the right one is inlet port, which is connected with high pressure directly, while the left one is outlet port, which is connected with the motor's piston. The high pressure from inlet port is able to enter the center of the hollow sleeve without any resistance. Coil A (the left coil) of the electromagnet should be normal energized to resist the rightward force under this high pressure.

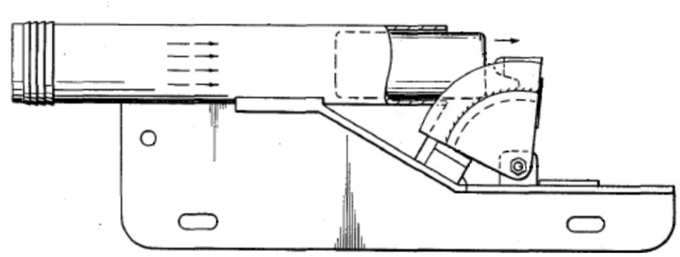

Fig.1. Structure of ROV carried underwater hydraulic ejection system

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During opening process, coil B (the right coil) of the electromagnet is energized, the valve sleeve will move rightward to connect the pressure oil with its outlet port. Owning to the moving sleeve structure, the valve body could support most leftward steady flow force for the moving sleeve. The direction of transient flow force is rightward, which would help the electromagnet to open the valve port, because the leftward flow rate is continuously increasing during the opening process. During closing process, coil A is energized, and the valve sleeve will move leftward to disconnect the pressure oil with its outlet port. The direction of steady flow force is still leftward to help the valve's closing, while the direction of transient flow force would also change to leftward, because the leftward flow rate is continuously decreasing. The opening process would be a little bit slower than the closing process due to the steady flow force, but still faster than traditional solid core valve spools, especially for large flow rate high-speed on/off valves.

Owning to the moving sleeve structure, the valve body could support more than 70% of steady flow force for the moving sleeve, and the transient flow force could help the sleeve to open the valve port due to the flowing-out type valve port. The parameters at this valve port is shown in Fig.3. The flow rate of this flowing-out type valve port is:

$$Q = C_q A_0 \sqrt{\frac{2\Delta P}{\rho}} = C_q A_0 \sqrt{\frac{2(P_1 - P_2)}{\rho}} \tag{1}$$

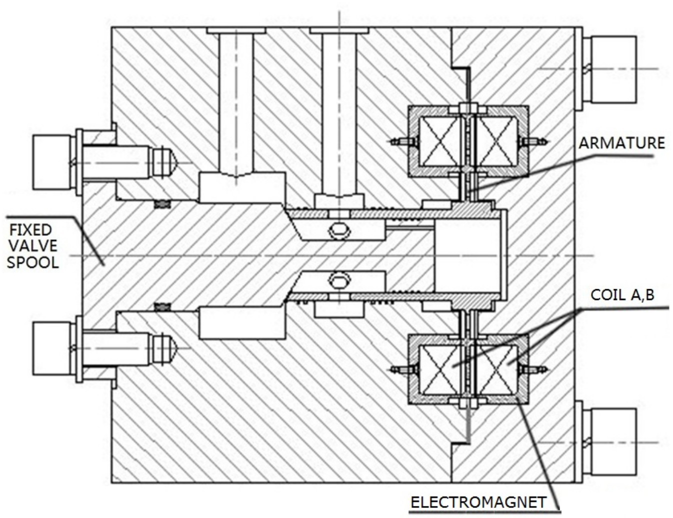

Fig.2. Structure of double spool type on/off valve

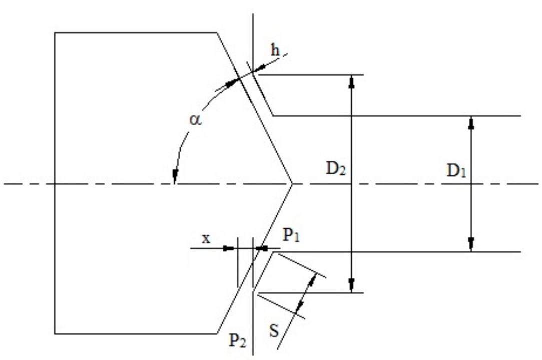

Fig.3. Parameters at the flowing-out type valve port

In which, C_q is the flow-rate gain of valve port. Δp, P_1 and P_2 are the pressure decrease, inlet and outlet pressure of the valve port, ρ is the density of fluid. A_0 is the effective area of valve port, which can be calculated from its average diameter dm as follow:

$$A_0 = \pi d_m x \sin\alpha \left(1 - \frac{x}{2d_m}\sin 2\alpha\right) \tag{2}$$

$$d_m = (D_1 + D_2)/2 \tag{3}$$

In which, α is the conical degree of the poppet valve, x is the opening of the valve port, d_m, D_1 and D_2 are the middle, internal and external diameter of the poppet valve port. To meet the UHES' demand (Q=60L/min, transitional time 2ms), these parameters are designed as: α=60°, D_1=18mm, D_2=21.5mm, and x=0.5mm.

B. Modeling and simulation results

The simulation model of this double spool type on/off valve with flowing-out type valve port is shown as Fig.4. The parameters of this double spool type on/off valve is shown in Table I. Since the moving part had been changed into the sleeve, the relatively moving component had also been changed into component 1, 2, 3, and 7 in Fig.4. All these components are all connected with the electromagnet force and mass block, while the fixed spool (center part) is connected with a fixed point at its right end. Fig.5 shows the static load characteristic of this double spool type on/off valve.

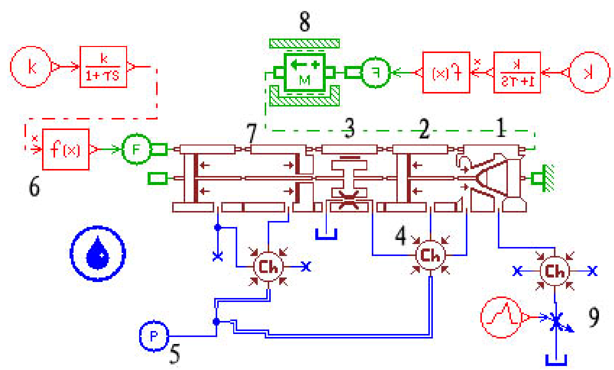

Fig.4. Simulation model of the double spool type on/off valve

1-Poppet valve, 2-Piston, 3-Leakage, 4-Chamber, 5-Constant pressure supply, 6-Driving Force, 7-Movable part, 8-Mass of sleeve, 9-Variable load

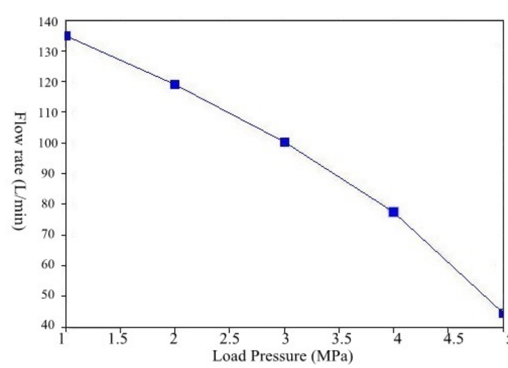

Fig.5. Static load characteristic of the valve port

TABLE I. PARAMETERS OF THE DOUBLE SPOOL TYPE ON/OFF VALVE

Name of Parameters	Unit and Value	
	Unit	***Value***
Flow rate gain	--	0.8
Diameter of valve port	mm	18
Diameter of fixed valve spool's rod	mm	7.68
Conical semi-angle degree on the sleeve	°	60
Conical semi-angle on the fixed spool	°	65
Contact length	mm	11.5
Valve spool's maximum movement	mm	0.5
Mass of the moving sleeve	g	95
Volume of variable chamber	cm^3	50
Density of fluid	Kg/m^3	860
Viscosity	N/(m/s)	0.8
Clearance between spool and sleeve	mm	0.02

The dynamic character, especially the opening time, is influenced by the mass of the moving sleeve greatly. Fig.6 shows the step response of flow rate while the mass of sleeve is 45g, 65g, 95g and 125g respectively. The lighter the sleeve is, the quicker response it has.

C. *Steady flow force on the valve*

The on/off valves for UHES should support large flow rate in very short transitional time. In this case, the steady and transient flow force had become the main barriers to increase the on/off valves' response. Due to the law of conservation of momentum, the steady flow force on the fixed valve spool is:

$$F_s = \rho Q v_2 \cos\alpha = C_Q \pi D_m x p_s \sin 2\alpha \tag{4}$$

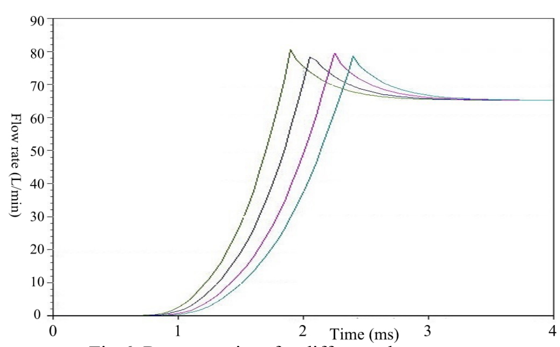

Fig.6. Response time for different sleeve mass

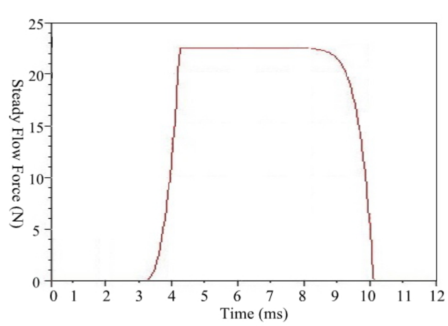

Fig.7. Steady flow force on the central valve spool

In which, ρ is the density of fluid, C_Q is the flow-rate gain of valve port, D_m is the middle diameter of valve spool, x is the opening of the valve port, p_s is the pressure decrease of the valve port, and α is the conical degree of the poppet valve.

The steady flow force on the fixed valve spool is shown in Fig.7, and the direction is rightward. This is also the total steady flow force value for the right side components of the throttle port, which includes the moving sleeve and the valve body. the direction is leftward.

Thank to the very thin size of moving sleeve, the low pressure's influence area had exceeded its external diameter to a great extend. Thus the steady flow force on the moving sleeve had decrease to its 30%. In one word, the valve body had supported more than 70% of steady flow force for the moving sleeve.

To analyze how much percent of steady flow force had been supported by the valve body, and how much percent are still acting on the moving sleeve, a Computational Fluid Dynamics (CFD) model based on FLUENT software is setup, which is shown as Fig.8.

Assume the inlet pressure is 1MPa, and the outlet pressure is 0, the pressure distribution inside the valve's chamber and valve ports at 0.5mm's opening is shown in Fig.9. The low-pressure-influence area is more than 3 times of the moving sleeve's effective area. Thus, the valve body had supported more than 2/3 of steady flow force for the moving sleeve.

The fluid speed inside the valve's chamber and valve ports at 0.5mm's opening is shown in Fig.10 (left). The high fluid speed area is almost the same as low-pressure-influence area.

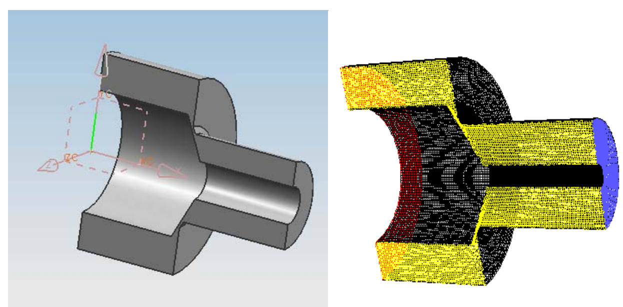

Fig.8. CFD model of the double spool type on/off valve

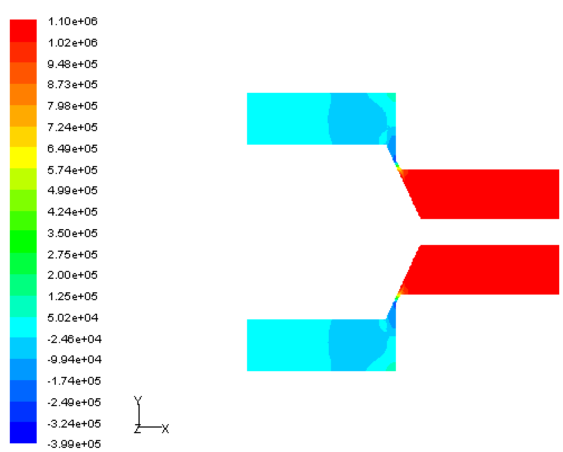

Fig.9. Pressure distribution inside the valve chamber at 0.5mm's opening

While the valves' opening decreased to 0.1mm, the high fluid speed area is becoming small. The fluid speed distribution is shown in Fig.10 (right). This means that the valve body had supported less percentage of steady flow force for the moving sleeve if the valve's opening is small. On the other side, the total value of steady flow force itself had also been reduced while the opening is small.

D. *Transient flow force on the valve*

The transient flow force is caused by the acceleration process of fluid in the valve chamber. This force is acting on both the fixed valve spool and the moving sleeve. While the fluid is flowing from the right port to the left port in Fig.2, the valve port is a flowing-out type port. While the valve port is opening, the acceleration of fluid is leftward and the direction of transient flow force is rightward, which is able to help the sleeve opening the valve port. The transient flow force is:

$$F_s = LC_d W\sqrt{2\rho\Delta P}\,\frac{dx_v}{dt} + \frac{LC_d W x_v}{\sqrt{\frac{2\Delta P}{\rho}}}\frac{d(\Delta P)}{dt} \tag{5}$$

In which, L is the length of valve chamber, A is the throttle area, ρ is the density of fluid, C_d is the flow-rate gain of valve port, W is the valve area gradient, □p is the pressure decrease of the valve port, and x_v is the opening of the valve port. The transient flow force on the moving sleeve is shown in Fig.11.

E. *Wet-type disc electromagnet based on double coil pairs*

To obtain larger magnet force to drive the moving sleeve in very short transitional time, the traditional solenoid-type electromagnet had been replaced by a wet-type disc electromagnet. Its driving force could be enhanced by 5 times at short distance. Instead of reset spring, a double coil pairs' structure is designed for the electromagnet to obtain larger closing force and faster closing speed. The parameters of the wet-type disc electromagnet is shown in Table II.

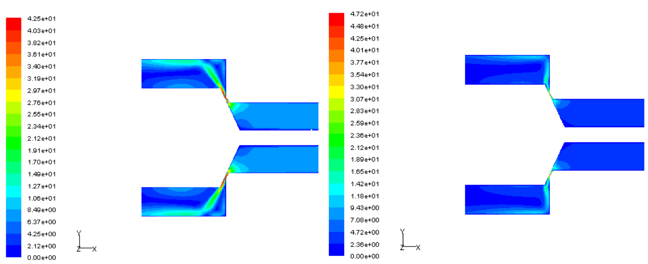

Fig.10. Fluid speed distribution at 0.5mm and 0.1mm's opening

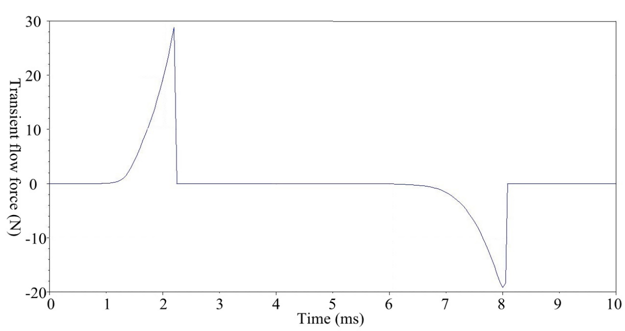

Fig.11. Transient flow force on the moving sleeve

TABLE II. PARAMETERS OF THE WET-TYPE DISC ELECTROMAGNET

Name of Parameters	**Unit and Value**	
	Unit	***Value***
Number of turns of the coil	--	195
Resistance of the coil	Ω	3.8
Area of magnetic poles	cm^2	1.67
Gain	--	48
Air gap	mm	0.5
Mass of armature	g	95
Armature's maximum movement	mm	0.5
Time constant	ms	1.2
Viscosity	N/(m/s)	0.8
Frequency of control signal	Hz	100
Magnetizing voltage	V	48
Magnetizing time	ms	2
Maintain voltage	V	3
Demagnetizing voltage	V	48
Demagnetizing time	Ms	1.7

III. SIMULATION AND EXPERIMENTAL RESULTS

A. *Simulation results*

The simulation model of the whole on/off valve (double spool type valve body + flowing-out type valve port + wet-type disc electromagnet) is shown as Fig.12.

Fig.13 is the flow rate (red curve) response to the magnetizing and demagnetizing voltage (green curve). The demagnetizing voltage is -48V, which is not fully shown in the figure. The maximum flow rate is 64L/min, the total opening time is 2.25ms and the closing time is 2.15ms.

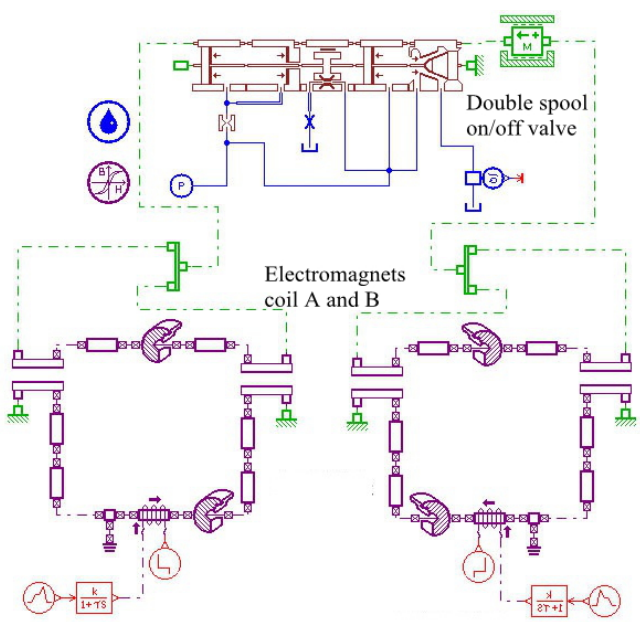

Fig.12. Simulation model of the whole on/off valve

The pure delay time at opening is 1.05ms, and 0.9ms at closing. This is due to the delay of electromagnet, residual magnetism, and friction.

B. *Experimental results*

The prototype of this double spool type high speed on/off valve with flowing-out type spool is shown in Fig.14. It had been tested in a test rig as shown in Fig.15. A pressure reduce valve is applied to control its input pressure, and a relief valve is used to simulate its load. The flow rate is measured by a turbine flow meter in the return pipe.

A PWM signal is created by a computer to control the high speed on/off valve. The average output flow rate is almost proportional with the duty ratio while the PWM's frequency is not higher than 25Hz, which is shown in Fig.16.

However, while the PWM's frequency is more higher, such as 50Hz or 100Hz, The proportional range of average output flow rate to the duty ratio is becoming smaller and smaller, which is shown in Fig.17.

IV. CONCLUSION

(1) The high speed on/off valves of UHES should be switched on and switched off once in each revolution.

(2) After the introduction of moving sleeve structure, the valve body could support more than 70% of steady flow force for the moving sleeve.

(3) The flowing-out type valve port changed the direction of transient flow force into a driving force, which is able to help the sleeve to open or close the valve port.

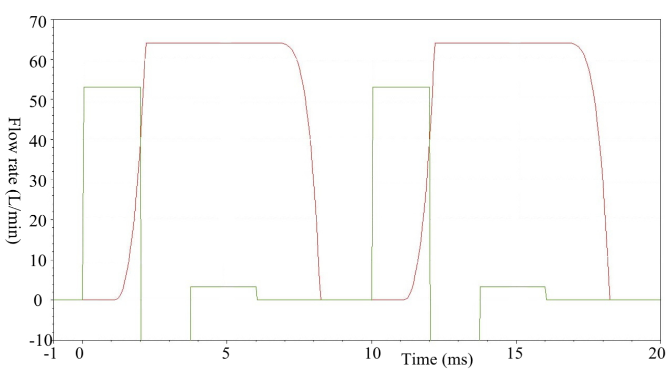

Fig.13. Response of output flow rate

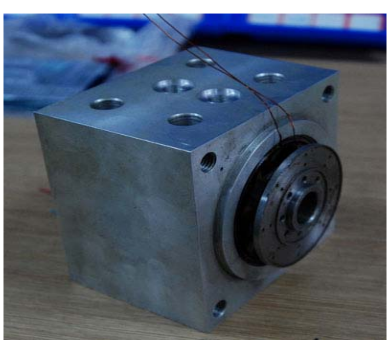

Fig.14. Prototype of the double spool type on/off valve

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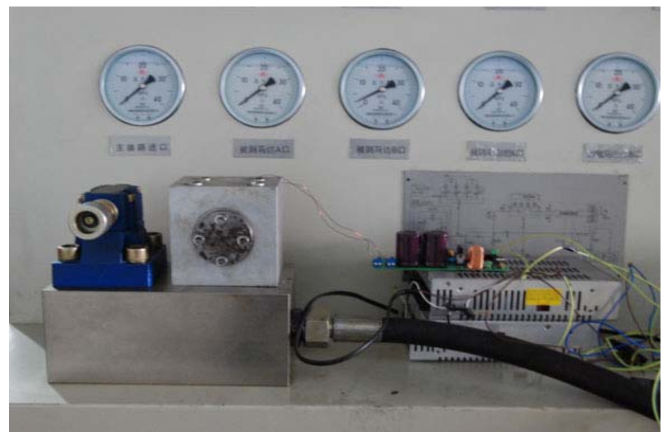

Fig.15. Test rig for the prototype of the double spool type on/off valve

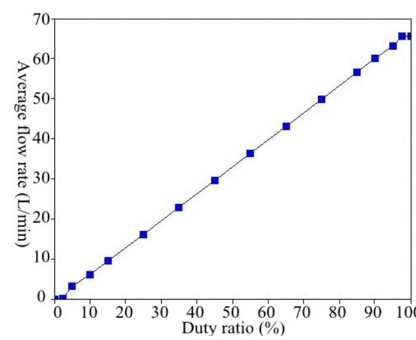

Fig.16. Average flow rate of the double spool type valve under 25Hz PWM

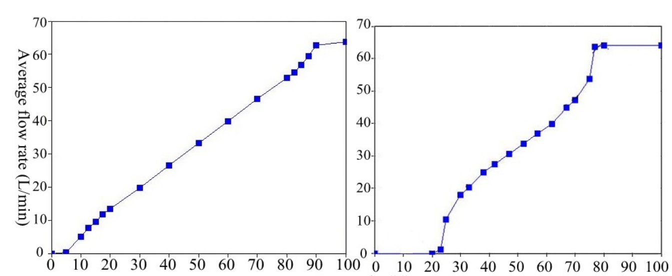

Fig.17. Average flow rate of the on/off valve under 50Hz and 100Hz PWM