Development of a Hydraulic Propulsion System Controlled by Proportional Pressure Valves for the 4500m Work-class ROV

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***Abstract*—Hydraulic propulsion system is widely used in remotely operated underwater vehicles (ROVs) especially work-class ROVs due to its high power density and strong work capability. In most hydraulic ROVs, the propellers are controlled by servo flow rate control valves or variable displacement motors. In this paper, a novel hydraulic propulsion system controlled by proportional pressure valves with rotational speed feedback is proposed, including new-material thrusters and adaptive electronic control units (ECUs) which can work properly in the high-pressure oil. The proportional pressure control system has a much lower cost and a higher efficiency compared with servo valve control systems. And its response is still quick enough to control the underwater vehicles' attitude compared with variable displacement control system. Moreover, it can reduce the influence on the vehicle dynamics caused by the dead-zone and hysteresis of the proportional valves due to the rotational speed feedback. This paper describes both the design and technical integration of the deep water proportional-pressure-controlled hydraulic propulsion system, including hydraulic and electronic elements. Additionally, the simulation and in-water tests of several key elements such as the thrusters and hydraulic pump are presented. Both the simulation and experiments results show that the closed-loop propulsion system has a fast response with high precision.**

Keywords—hydraulic propulsion system, proportional pressure reducing valve, ECU, thruster, speed feedback

I. Introduction

ROVs are playing a major role in ocean engineering and science research, which makes them become an important part of our society. During the recent two decades, exploring deep sea with ROVs has been becoming a focus of marine research. As the ocean attracts great attention on environmental issues and resources, the need for and use of underwater robotic system has become more apparent [1]. Since 2008, a national high technology project named "4500 Meters Class Deep-sea Operation System" has been started by the Chinese Government. The main objective of project is to develop a work-class ROV which will perform scientific tasks on the seafloor to depths of 4500m. The ROV will be installed on the "haiyang 6", a support vessel which is currently operational.

Figure 1. Overall view of the vehicle

Hydraulic propulsion system is widely used in ROVs especially work-class ROVs. Compared with the electrical motors, hydraulic actuators have a higher speed of response with fast starts, stops and speed reversals [2]. And torque to inertia ratios in hydraulic system are large with resulting high acceleration capability, which will substantially improve the control performance. In most hydraulic ROVs, the methods to control propeller can be divided into two parts. One is the servo valves control while the other is proportional valves control. Servo valves are popular in propulsion system due to their high precision and quick respond [3-4]. However, no commercial servo valves are available at the depth of 4500m. Compared with servo valves control system, the proportional pressure

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control system has a much lower cost and a higher efficiency. Moreover, proportional valves are more adaptive to the water depth and the oil pollution. Though proportional control system is a much more simple way, it will affect the control accuracy due to the dead-zone and hysteresis of the proportional valves.

Besides traditional valve control methods, several new kinds of hydraulic propulsion system has been proposed [5-6]. However ,there are still some problems to hinder their application. In this paper, a novel hydraulic propulsion system controlled by proportional pressure valves with rotational speed feedback is proposed. The propulsion system is specifically designed to fill the needs of the 4500m work-class ROV ,which will be capable of performing a wide variety of tasks where large payload and good manipulative ability is required. The thrusters are driven by fixed displacement hydraulic motors respectively with a gear inside which makes it convenient to measure the rotational speed. Due to the rotational speed feedback , it can reduce the influence on the vehicle dynamics caused by the dead-zone and hysteresis of the proportional valves.

This paper describes both the design and technical integration of the deep water proportional-pressure-controlled hydraulic propulsion system, including hydraulic and electronic elements. During the design and construction phase, keeping the components easy to maintain or replace is given a high priority so that they could be improved or expanded upon. All these considerations led us to build a robust ,energy efficient system with high precision. It is important to mention that the hydraulic propulsion system has been completed and most of elements have been tested in water.

II. HYDRAULIC PROPULSION SYSTEM

A. System Overview

The schematic diagram of the hydraulic propulsion system is shown in Fig.2. It mainly consists of two variable displacement pumps, paired valve packs and eight thrusters. Each valve pack has one electronic control unit (ECU) inside so that all the thrusters can be controlled synchronously. As the control signal to ECU changes, the rotational speed of the thrusters can be accelerated or decelerated respectively.

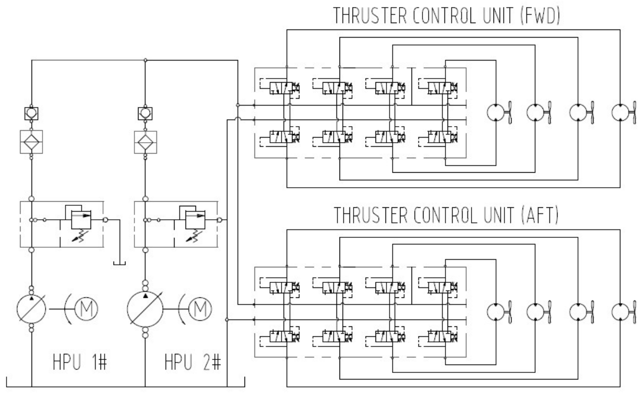


Figure.2. Schematic diagram of the hydraulic propulsion system

The hydraulic power is from two axial piston variable displacement pumps with constant pressure control. Both of them are driven by underwater motors with 65 horsepower. The supply pressure is maintained at about 20MPa, while the relief valves are set a little higher to ensure the system safety.

The thrusters are driven by fixed displacement hydraulic motors in which rotational speed sensor is integrated . Using simplified propeller torque and thrust coefficient which is experimentally related to the speed of advance of the propeller[7], The output torque Q of hydraulic motor and the propeller thrust T at steady state can be defined as:

$$Q = PD_m = K_Q \rho n^2 D^5 \tag{1}$$

$$T = K_T \rho n^2 D^4 \tag{2}$$

In which, P is the pressure difference of inlet and outlet ports, D_m is the displacement of motor, K_Q is the torque coefficient of the propeller, K_T is the thrust coefficient, ρ is the density of water, n is the rotational speed, D is the diameter of the propeller.

From the equations above, it is easy to obtain:

$$T = \frac{K_T}{K_Q}\frac{Q}{D} = \frac{K_T}{K_Q}\frac{D_m}{D}P \tag{3}$$

As the displacement of the motor Dm is a constant, the hydraulic propulsion system is essentially a torque-controlled system. For the given propeller, the thrust is approximately proportional to the motor pressure difference as well as the torque. The pressure difference P is controlled directly by paired proportional pressure reducing/reliving valves. With no current applied to the solenoid, the valve will maintain pressure at approximately 100 psi(0.69MPa). When the coil current of one valve is higher than the other, a differential pressure generates. If the torque caused by the differential pressure is high enough to overcome the friction and the water resistance, the propeller will be accelerated and the thrust generates. Therefore, the rotational speed and thrust of the propeller can be controlled through changing the control currents of the valve coils by ECUs.

B. Thrusters and Control Valves

The 4500m ROV has eight hydraulic thrusters, four of which are equipped in the horizontal plane while the remaining are decorated in the top plane maintaining 10 degrees to the side plane. With the configuration of thrusters shown in Fig.3, The propulsion system can produce a forward/lateral thrust of 920kgf and a vertical thrust of 780kgf.

The thruster characteristics may greatly influence the system dynamic [8]. To improve the thrust performance and make the size compact, the thrusters need special design. Fig.4 shows the main structure of the thruster which includes a shroud, a motor and a 3-blade propeller. The hydraulic motor has a long axis so that the propeller can be installed on the axis directly. And the shroud is made of a new kind of reinforced nylon which has a low density and a high strength.

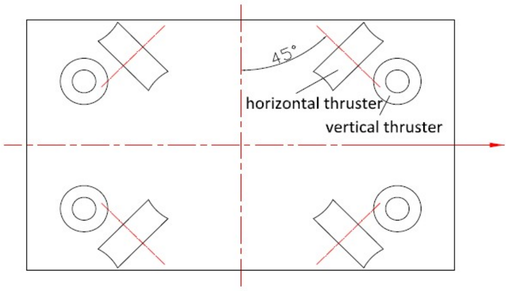
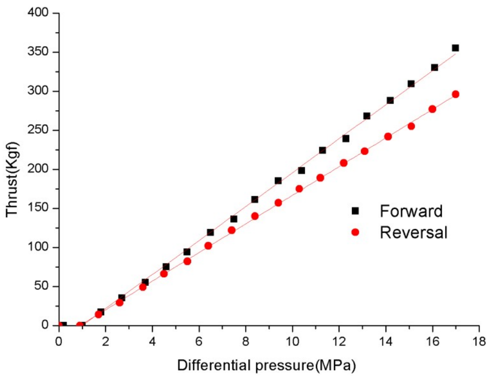


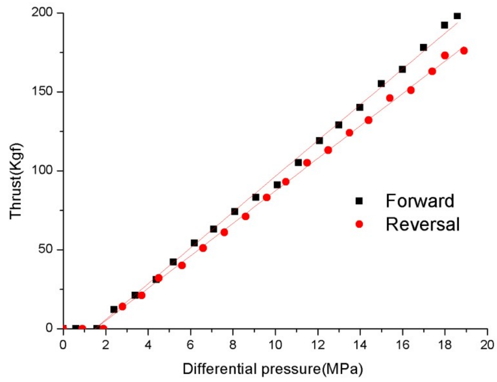
Figure.3. Top view of thrusters configuration

Figure.4. The 16” thruster installed on ROV

The thrusters have 2 sizes: 12” used in vertical plane and 16” used in horizontal plane. The 12” one is driven by 23cc/r motor while the 16” one is driven by 56cc/r motor. Both of them have the similar structure and the maximum rotational speed exceeding 1000rpm which will decrease the angle of advance and increase the thrust coefficient. As a result of frictional resistance of the hydraulic motor, both of the thrusters have a dead zone as shown in Fig. 5.



(a) 16” thruster



(b) 12” thruster

Figure.5. Linear fitting of differential pressure versus thrust

Figure.6. Thruster valve pack

From the curve of thruster characteristics, it is easy to obtain that the thrust is proportional to the differential pressure as well as the torque produced by the motor. In addition, the reversal thrust is close to the forward thrust which makes the ROV have better control performance and higher efficiency in any moving direction.

To keep the hydraulic components easy to maintain or replace, two valve packs were designed. Valves are mounted horizontally to maintain oil in the armature preventing trapped air instability (See Fig.6). Each valve pack has 8 proportional pressure valves from HydraForce company which are all the same size. As the pressure of motor inlet and outlet ports are controlled by the proportional pressure valves, the valve characteristics ultimately governs the control performance. The 3-way proportional pressure valves in this system have two working modes: reducing and reliving. If the motor remains stationary, Both of valves are working in the reducing mode. If the propeller is running which means that large flow rate generates, the inlet valve is working in reducing mode while the other is in reliving mode.

Although the response of these valves is still quick enough to control the underwater vehicles' attitude compared with variable displacement control system, the influence on the vehicle dynamics caused by the dead-zone and hysteresis can not be neglected. Therefore, the rotational speed feedback is proposed. The 7-teech gear inside the hydraulic motor makes the closed-loop control easy to realize. The rotational speed sensor is a hall sensor which can still work properly in high pressure.

C. Hydraulic Power

Variable displacement pumps are used in most hydraulic ROVs to save energy and reduce the heating of oil. In order to improve reliability, the vehicle has two such kind of pumps. So the system can still work without resurfacing if one failed. Each pump is driven by a 3000VAC underwater motor, the rotational speed of which can reach as high as 3000rpm. Fig.7 shows the structure of hydraulic power unit. The Rexroth pump are coupled directly with the motor coaxially.

The control type of pump is pressure remote control and it has two pressure levels due to two different pressure relief valve. The low pressure level is usually used to check the thrusters control circle during deck test, while the high pressure is needed in normal working condition.

Figure.7. Hydraulic power unit

The displacement of the primary pump is 45cc/r while the secondary is 71cc/r. The setting pressure of the small size pump is a little higher to avoid pressure vibration of two pumps. The maximum hydraulic power supplied by the small pump is right at the rated power point of the underwater motor, while the large pump may make the motor overload. Therefore a power valve is added to limit the maximum output power of the large pump. Compared with only pressure control, HPUs can provide more flow rate when the vehicle is working in a ocean current.

D. Electronic Control Unit

The electronic control unit is an important part of ROV control system. It can receive the RS-485 control signal from the main electrical container and control the eight proportional valves simultaneously. It is installed in valve pack and consists of two parts which is shown in Fig.8. The main board has an ATmega1280 microcontroller and a special pressure-resistant crystal oscillator. Each amplifier driven by the main board can control two proportional valves respectively. ECU also drives a two-way solenoid valve in pump control circle, allowing the operator to choose high or low pressure level.

Figure.8. Electronic control unit

The propeller speed closed-loop control diagram is shown in Fig.9. The speed signal is from rotational speed sensors inside the thruster. The feedback is a frequency signal, so a frequency-to-voltage module is added in ECU. To improve reliability, ECU can work in closed-loop or open-loop model so that the system can still work properly without resurfacing if one of the rotational-speed sensors is failed.

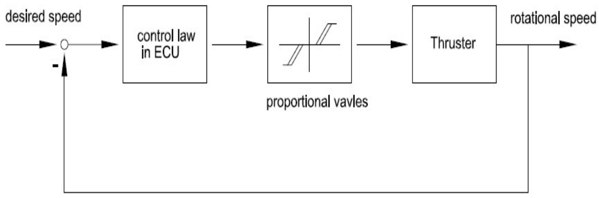


Figure.9. Propeller speed closed-loop control diagram

III. SIMULATION AND EXPERIMENT RESULTS

A. Simulation

A simulation model is built to study the characteristics of the propeller speed control system in the AMESim (See Fig.10). The model can be divided into four parts: hydraulic power source, thruster, proportional pressure valve and the control system. The flow rate of the pump is sufficient to keep the supply pressure stable. And a PID controller with saturation is used. The parameters used in simulation are shown in Table 1.

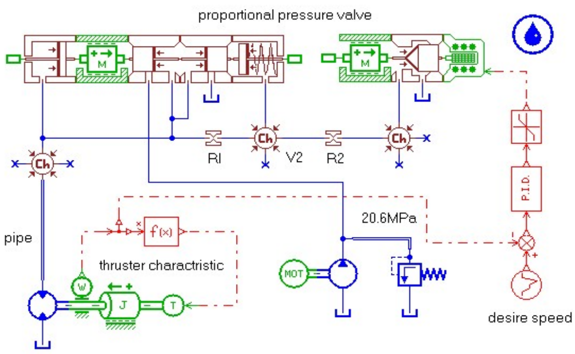


Figure.10. Simulation model of propeller speed control system

TABLE I. PARAMETERS OF HYDRAULIC PROPULSION SYSTEM

Name of Parameters	**Unit and Value**	
	Unit	***Value***
Fluid density	850	Kg/m3
Fluid viscosity	51	cP
Fluid bulk modulus	700	MPa
System pressure	20.6	MPa
Orifice diameter of R1&R2	0.5	mm
Oil chamber volume V2	2	cm3
Main valve spring stiffness	1.11	N/mm
Main spool mass	10	g
Preload spring force	14.43	N
Motor displacement	56	ml
Motor mechanical efficiency	0.95	--
Motor volumetric efficiency	0.96	--
Total moment of inertia	0.04	Kg·m2

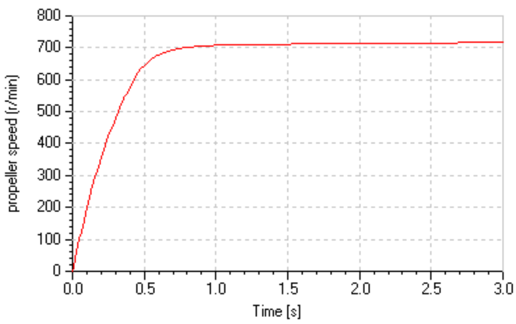


Figure.11. Step response of the propeller speed

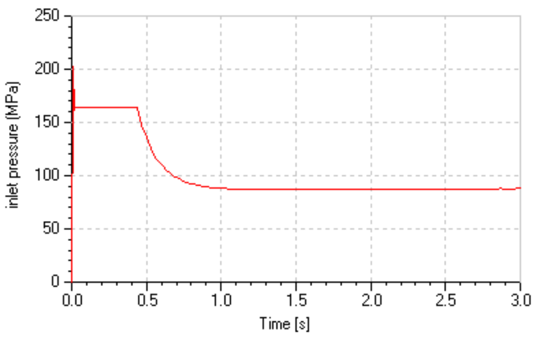
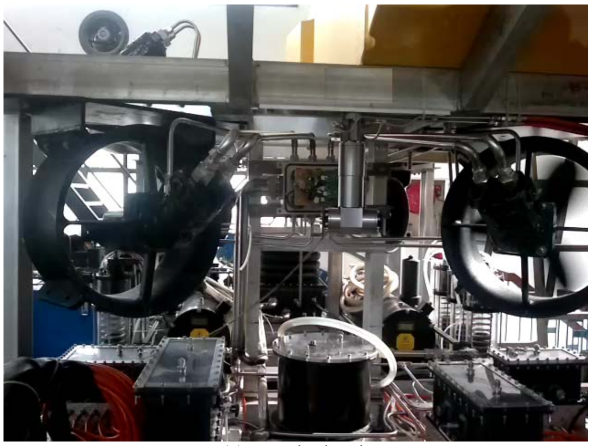


Figure.12. Pressure response of the motor inlet pressure

The ultimate goal of the rotational speed control is to obtain a good tracking performance of the desired input. To decrease the steady-state error and improve the stability, a PI control method is used. The simulation results are shown in Fig.11 and Fig.12, where the desired speed is 720 r/min, Kp is 1 and Ki is 0.05. From the step response of the propeller speed, it takes only 0.7s to reach 700 r/min which is about 70% of the maximum rotational speed. As most ROVs have large inertia, the dynamic response is fast enough. Fig.14 shows the motor inlet pressure response curve. when the speed is far away from the desired speed, the inlet pressure keep saturated to get maximum acceleration. After that, the pressure drops to the steady-state operating point smoothly. The simulation results prove that the closed-loop control system has a fast response with high precision.

B. *Experiment Results*

According to the schematic diagram shown in Fig.2, The hydraulic propulsion system is established. Fig.13 shows the air test and pool test of the system. The hydraulic system has a compensated reservoir and 6 compensators so that it can still work properly underwater. As the whole ROV control system is not completed ,only the hydraulic power unit and single 16” thruster are tested. The experiment data is acquired by Advantech USB-4711, the sampling interval is 1ms.



(a). Test in the air

(b). Pool test

Figure 13. Tests of hydraulic propulsion system

As all the hydraulic power comes from HPUs, the pressure test is carried out first. The system pressure response curve is shown in Fig.14. It is obtained by controlling the solenoid valve via ECU commands. The pressure has two levels so that it can ensure safety and save energy in the case that high pressure is not required. The low pressure is set at about 6MPa, at which the pan and tilt system can still work properly. The pressure response is very fast and stable. And it only takes about 0.3s to establish the system pressure.

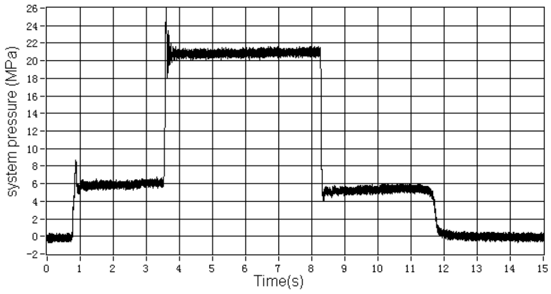


Figure 14. Hydraulic system pressure response

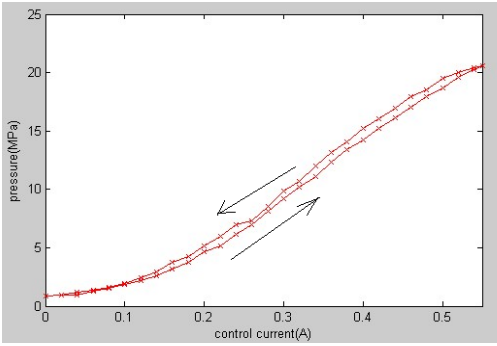


Figure.15. Reducing pressure characteristic in open-loop control

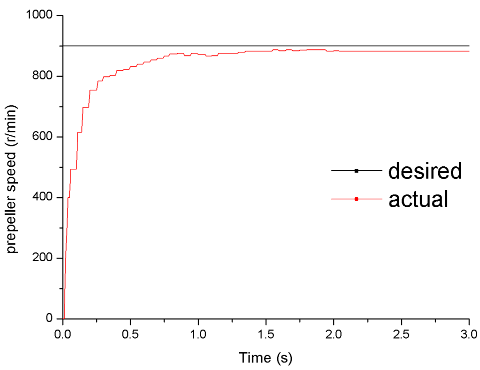


Figure.16. The 16” propeller speed response

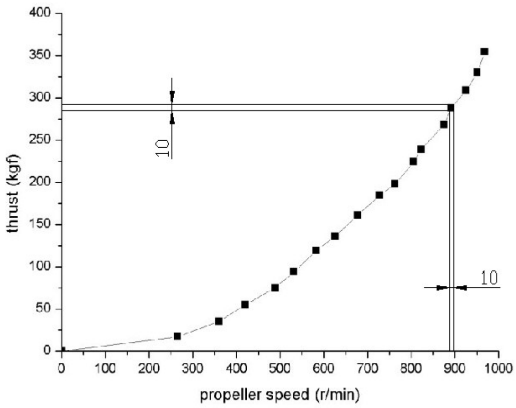


Figure.17. Thrust vs. propeller characteristic of the 16” thruster

Fig.15 shows the test result of valve characteristic in open-loop control. The valve has about a 20% dead zone and pressure uncertainty of 0.8MPa at the same control current. According to the line fitting in Fig.5, it will lead to a thrust error of about 20Kgf.

The 16” propeller speed response curve is shown in Fig.16. It takes about 0.9s to reach 900 r/min. An error range of 10 r/min in propeller speed almost has no influence on the thrust as well as the vehicle dynamic. The thrust error is about 10kgf at 900 r/min (see in Fig.17). As the thrust is proportional to the square of the propeller speed, it is even smaller at the lower speed, which is especially important for ROV during important operations like combined vehicle-manipulator control. It is proved in the experiment that the speed closed-loop control system has a better performance.

IV. CONCLUSION

The paper introduces a hydraulic propulsion system controlled by proportional pressure reducing valves. And the rotational speed feedback is added to reduce the influence on the vehicle dynamics caused by the dead-zone and hysteresis of the proportional valves. The four parts of the system: thrusters, control valves, hydraulic power and ECU are describe in details. All of the hydraulic components including two-pressure-levels hydraulic power units(HPUs) and proportional valves are controlled by RS485-based ECUs in the valve packs filled with compensated oil.

The simulation shows how the speed closed-loop control system works. A PI controller with saturation is quite suitable for the system. To study the system characteristics with the closed-loop control, several experiments are carried out. The results prove that the system has a stable system pressure with quick response and the operator could choose the high or low pressure level according to the vehicle working condition. Moreover, the speed closed-loop control system has higher precision compared with open-loop control. A future objective is the pool test of the whole system including the hydraulic system, the electronic container and the umbilical cable with optical fibres. This ROV is scheduled to start its first sea trial in South China sea in June,2014.

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