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Design and Modeling of Oceanographic Environment Adaptive Variable Pumps

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ABSTRACT Variable pumps are important hydraulic power units in deep-sea exploitation due to their good energy-saving and high precision capabilities. However, their application in such hostile environment suffers from the risk of control failure. Moreover, developed throughout trials and error in onshore simulation experiment, it is thus not just a time-consuming and expensive task but also required to implement an adaptive scheme capability to be used in deep-sea application. In this paper, a self-adaptive pressure sensing scheme and a novel close-loop control structure involved oceanographic environment adaptive variable pump (OEAVP) are proposed to autonomously adapt to the variable seawater conditions. Furthermore, based on environmental and fluid models, dynamic performances of the OEAVP model for pressure and flow-rate controls are analyzed. MATLAB/Simulink pack tool is used to perform the OEAVP system stability and comparative deep-sea water and shallow-water stability control are addressed. It reveals oceanographic environment influences on control performances of OEAVP from the direct effect of ambient pressure and the indirect effect of hydraulic fluid properties changes. Ultimately experimental tests including SPSS performances, control characteristics and dynamic responses of OEAVP's are performed in a simulation hull, which demonstrates consistent performances in oceanographic environment and confer to the proposed OSVP with high adaptive capability.

INDEX TERMS Oceanographic environment, variable pump, self-adaptive sensing scheme, control characteristics, system stability.

I. INTRODUCTION

With the rapid developments of ocean exploitation [1], [2], e.g. marine surveying, ocean mining and submarine oil and gas exploitation, deep-sea operating equipment depends on strong power drives with high performances including high power density, large force/torque capabilities, faster response and superior speed regulation. Hydraulic power units (HPUs) are treated as potential effective power. However, applied in ocean environment, HPUs face lots of serious challenges. In ocean surrounding, ambient pressure increases about 1 bar every 10 meters of depth. Compared with sea surface, in the depth of 5000m seawater, ambient pressure is about 50MPa and it is more than 500 times atmospheric pressure, meanwhile deep-sea temperature is approaching 1°C which is far lower than the average temperature of sea level of 15°C [3].

The extreme oceanographic conditions cause a great barrier for power supply of subsea hydraulic system. To reduce the effect of ambient pressure of seawater, two engineering methods are adopted. The first utilizes a pressure-resistant housing to resist the high pressure and protects HPUs to work in an atmospheric environment [4], [5]. This is an ideal approach for transplanting land-used HPUs, but will lead to a dramatic increase of the thickness and weight of the housing with the deepening of seawater. The second alternative is called as pressure compensation method [6], [7], that is a moveable and well-sealed elastic element or piston developed and mounted on surface of reservoir to connect with seawater, due to low compression of hydraulic medium, by movement of the elastic element or piston pressure of seawater is introduced as the internal fluid pressure of reservoir. This scheme

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is widely used in ocean, and such HPUs can be found in Perry power pack [8], and Forum products [9]. However, suction pressure of pump of HPUs is raised to the ambient pressure of seawater, which will change physical properties of fluid such as the viscosity and the bulk modulus, and the results in the initial measurement methods in closed-loop control system of pressure and flow-rate applied in atmospheric conditions no longer work, especially for feedback lines. The changes of working environment and feedback lines will produce significant adverse impact on the pump performances and its control system structure.

Since physical parameters of fluid are sensitive to environmental variables [10], [11], such as temperature and pressure, especially fluid viscosity changes with temperature [12], [13]. Those changes will induce a big influence on pump performances [14], [15]. The test results in the depth of 6000m deep-sea as shown in [10], the compressibility of hydraulic fluid will reach up to 3.6%, its viscosity will increase 17.7 times compared with atmospheric condition. In [16], two kinds of constant pump are tested in high-pressure fluid-immersed environment, which represents the steady-state performances varying with discharge pressure of pump are similar as in the atmospheric condition. In fact, temperature ranges in the test is fixed as 27∼65°C rather than the real oceanographic environment as above-mentioned, so fluid properties changes are underestimated especially on lower temperature, therefore there is an obvious deviation about the evaluation of pump performances. In addition, although multiple environmental variables such as the ambient pressure, the temperature, the ocean current, etc. simultaneously affect the changes of fluid properties and further influence on the discharge pressure and the output flow-rate of hydraulic system. Most focus is oriented on the single variable acting on the pump performances rather than the compound effect. This is not enough to reveal operation performances in real deep-sea conditions where ambient pressure and seawater temperature are constantly changing and inseparable.

Closed-loop control structure of variable displacement pump (VDP) should be improved for the development of deep-sea HPUs. Differing from atmospheric environment where suction pressure is equal to tank's pressure which is constant, the pressure in tank by pressure compensation varies with ocean depth, which can cause the discharge pressure to also raise up. If still seen this varying discharge pressure as the feedback of closed-loop pressure control, will definitely fall into chaos for the control system in varying depth.

Therefore, developing closed-loop controlled with variable system adapted to ocean environment is an imperative task. Although several advanced control technologies for VDP are applied, such as linear control method [17],load sensing systems [18], [19],adaptive and nonlinear control [20],etc., this study emphasizes on environmental adaptability of the VDP,learns from robust control methods in [21], and analyzes its performances from the changes of fluid properties and oceanographic environment.

The contributions of this paper include: To introduce ambient pressure from seawater as a new feedback line, and combine with discharge pressure to build a self-adaptive pressure sensing scheme (SPSS). Based on the sensing method, a deep-sea pump called as oceanographic environment adaptive variable pump (OEAVP) with novel close-loop control structure is designed. Underlining oceanographic environment model and fluid model, dynamic control models of OEAVP are obtained. Then analysis of control characteristics and system stability are completed in variable ocean depths. Performance experiments in deep-sea imitation hull are completed to test the SPSS performances, the control characteristics and the dynamic responses of OEAVP in oceanographic simulation hull.

II. DESIGN OF OCEANOGRAPHIC ENVIRONMENT ADAPTIVE VARIABLE PUMPS (OEAVP)

A. OVERALL STRUCTURE OF DHPU

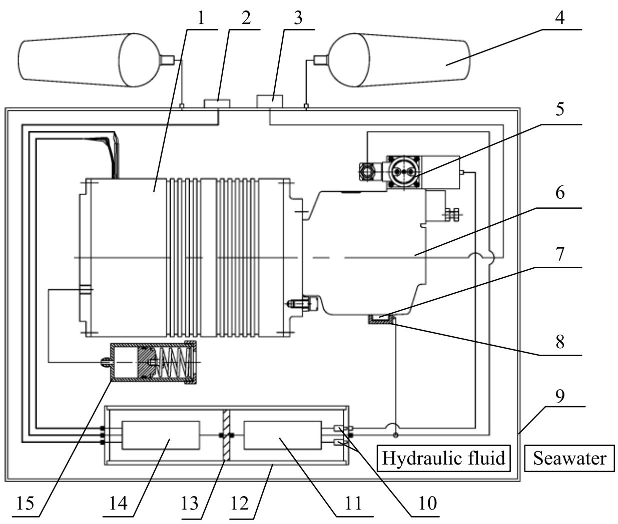
The overall structure of deep-sea hydraulic power unit (DHPU) is shown in Fig.1, and consisted of a variable displacement pump 6 controlled by a servo valve 5, a driving motor 1 with a piston-type pressure compensator 15, a pressure-resistant housing 12 protecting electrical components 11 and 14 from high-pressure surroundings, and a reservoir tank 9 equipped with a bag-type pressure compensator 4. All elements except for the compensator 4 are sealed into the tank 9 filled with hydraulic fluid. In ocean environment, seawater pressure acts on the compensator 4 and drives pre-filled fluid into the tank. According to hydrostatic transmission, internal pressure of fluid keeps a dynamic balance with seawater pressure thus effectively preventing tank to collapse with the increase of ocean-depth. Meanwhile, since the tank-wall is thin, seawater temperature is easily transferred to the hydraulic fluid in tank. Therefore, the environmental parameters of fluid are the same as in the deep-ocean surroundings. A variable displacement axial piston pump is employed as the deep-sea hydraulic power, while it should autonomously adapt accordingly to the changes of ocean depth. For this reason, the critical hydraulic pump is also called oceanographic environment adaptive variable pump (OEAVP). As the most important component of DHPU, the following concentrates environment adaptive designs of OEAVP.

B. SELF-ADAPTED SENSING METHODS FOR OEAVP

To achieve high-precision controls of OEAVP, feedback frames of signal sensing should be constructed to serve closed-loop control of hydraulic system. Therefore, feedback lines of pressure and angle need to be designed to work efficiently in oceanographic environment.

1) SELF-ADAPTIVE PRESSURE SENSING SCHEME IN OCEAN

Discharge pressure is taken as feedback for closed-loop pressure control of variable pump in traditional hydraulic control system [21]. Because above-mentioned pressure-compensated methods are utilized in DHPU, suction pressure



1.Electric motor 2. Interfaces 3. Hydraulic ports 4. Bag-type compensator 5. Servo valve 6. Variable displacement axial piston pump 7. Angle sensor 8. Pressure-resistant hull 9. Reservoir tank 10. Pressure sensors 11. Closed-loop amplifier 12. Pressure-resistant housing 13. Isolated plate 14. Motor driver 15. Piston-type compensator

FIGURE 1. **Overall scheme of DHPU.**

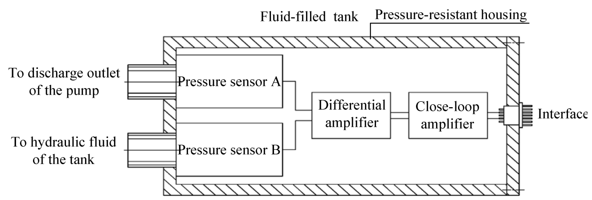


FIGURE 2. **Block Sketch of SPSS.**

and discharge pressure of pump are all superimposed with seawater pressure. To eliminate these adverse effects from oceanographic environment, relative pressure is proposed, and treated as the feedback pressure.

$$p_f = p_r = p - p_h \tag{1}$$

where, p_f, p_r, p and p_h are feedback pressure, relative pressure, discharge pressure of pump and seawater pressure at the ocean-depth h, respectively.

The feedback pressure in (1) as a relative value is not affected by seawater pressure in variable ocean-depth, it is self-adapted to oceanographic environment. This pressure sensing method satisfies signal feedback requirements of pressure control system, and can be applied in full depth.

In deep-sea practice towards the above-mentioned feedback line, pressure resistance of sensors is another problem to resolve. Although adopting pressure tolerant design [22] can protect sensitive sensors through soft casting, which the fabricating process is complex, and long-term pressure tests should be performed to guarantee their durability [23]. To overcome these disadvantages, a self-adaptive pressure sensing scheme (SPSS) is designed, shown in Fig.2. A pressure-resistant housing made up of aluminum alloy (7A09) protects sensitive components from high-pressure environment. The ratio between wall thickness Δh and the biggest internal dimension $l_{\max}$ of the housing under external pressure p_h is given as [24]

$$\frac{\Delta h}{l_{\max}} = \sqrt{\frac{3 \cdot (3m+1) p_h}{8 \cdot m \cdot s_{\max}}} \tag{2}$$

where, m is the reciprocal of Poisson ratio and s_{max} is the maximum stress in the center of housing's wall.

This self-adaptive pressure sensing scheme (SPSS) is based on the equation (1), which composed of two pressure sensors and a differential amplifier. Both sensors are land-used with high precision and high reliability. One of them is utilized to measure discharge pressure of pump, and another one is employed to detect tank pressure. The differential amplifier performs calculations of differential and amplification to match with the input of closed-loop amplifier of pump.

2) FLOW-RATE PRESSURE-RESISTANT SENSING METHOD IN OCEAN

Regarding flow-rate feedback of axial piston pump, swash-plate angle is often seen as the feedback of flow-rate [25], whose value is referent to the vertical position of swash plate. Therefore, a measurement of this angle is only relevant with the reference position, and is not affected by seawater environment. To operate at high-pressure surroundings, a pressure-resistant housing is also adopted, shown the element 8 in Fig. 1.

C. CONTROL PRINCIPLE OF OEAVP IN VARIABLE OCEAN-DEPTH

Based on above-mentioned adaptive sensing methods for DHPU, closed-loop control principles for oceanographic environment adaptive variable pump (OEAVP) are established in Fig.3. Regulating process of the pump can be described as following: On input side of SPSS, discharge pressure of pump and tank fluid-pressure are collected. On output side, the relative pressure processed is matched with closed-loop amplifier. Via amplifier's conditioning, the processed signal drives the servo valve movement to regulate the opening of valve, and then pressure and flow-rate in control piston are controlled. By dynamic force balance with bias piston, discharge pressure and angle of swash-plate are tuned. Physical working principles are shown in Fig.5.

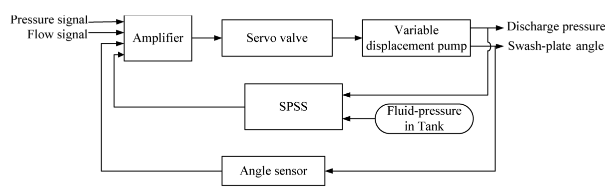


FIGURE 3. **Control principles of pressure and flow-rate for OEAVP.**

Since above controlling circuits of pressure and flow-rate have their own closed-loop feedback line, this hydraulic control system of the pump should be divided into pressure control and flow-rate control circuit.

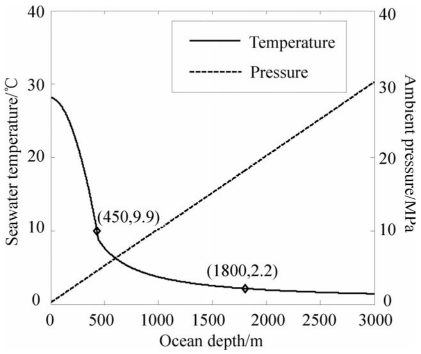


FIGURE 4. Environmental variables vary with the increasing of ocean depth.

III. MODELING ANALYSIS OF OEAVP IN VARIABLE OCEAN-DEPTH

A. MODELING OF EVAVP

1) SEAWATER ENVIRONMENT MODEL

a: AMBIENT PRESSURE IN OCEAN

If ocean depth is no more than1000m, ambient pressure can be expressed as [26]

$$p_1(h) = p_a + \rho_s gh + \frac{1}{2\rho_s} v_m^2 [1 - (\frac{v_s}{v_m})^2] \tag{3}$$

where p_a, ρ_s, v_s, v_{m} are atmospheric pressure, seawater density, seawater velocity at given depth and relative velocity of subsea equipment, respectively. h is the depth of sea.

If ocean depth is over 1000m, since the third term in above equation is very small, (3) then become

$$p_2(h) = p_a + \rho_s gh \tag{4}$$

b: SEAWATER TEMPERATURE IN OCEAN

Tropical sea is an important area for marine surveys, according to oceanographic curves recorded in [27], though piecewise fitting seawater temperature is written as

$$t_i(h) = \begin{cases} 1.96\times10^{-8}h^3 - 1.02\times10^{-4}h^2 & \\ -2.29\times10^{-3}h + 28.17 & h \in (0, 450) \\ 9337h^{-1.155} + 0.5226 & h \in (450, 3000) \end{cases} \tag{5}$$

where, $i = 1, 2$.

c: ENVIRONMENTAL MODEL IN OCEAN

Combining the equations (3), (4) and (5), the environmental model in the depth range of 0∼3000m are obtained.

$$S(h) = \begin{cases} p_1(h), t_1(h) & h \in (0, 450) \\ p_1(h), t_2(h) & h \in (450, 1000) \\ p_2(h), t_2(h) & h \in (1000, 3000) \end{cases} \tag{6}$$

From above model, variable ocean depth corresponds to different environmental model regardless of ambient pressure or seawater temperature in Fig.4. Changes of seawater temperature can be divided into three intervals: thermocline interval where steeply temperature gradient appears in 0-450m, decreasing temperature interval in 450-1800m, and stabilizing temperature interval in 1800-3000m. Their corresponding temperature drop is 4.2°C/hm,0.56°C/hm, and 0.027°C/hm, respectively. Variation of ambient pressure is approaching to proportional increase with ocean depth.

2) FLUID MODEL IN SEAWATER ENVIRONMENT

In OEAVP's analysis, two key parameters of hydraulic fluid involving viscosity and bulk modulus are concerned.

a: VISCOSITY

Bair's viscosity-temperature-pressure expression for petroleum-based fluid is widely adopted [28], and denoted as

$$\mu = K \exp[\frac{B}{t + C}] \exp(\alpha p) \tag{7}$$

where α is called dynamic viscosity coefficient, displayed as

$$\alpha(p, t) = \frac{1}{a_1 + a_2 t + (b_1 + b_2 t)p} \tag{8}$$

where, a_1, a_2, b_1, b_2, K, B, C are constants that related to specific hydraulic fluid.

b: EFFECTIVE BULK MODULUS

Compressibility of fluid is presented by the reciprocal of bulk modulus. To reveal the characteristic of fluid, the effective bulk modulus is adopted [29].

$$\frac{1}{E_e} = \frac{1}{E_c} + \frac{1}{E_l} + \frac{\chi}{E_g} \tag{9}$$

If dynamic varying process for gas is seen as an adiabatic process and the flowing pipelines used thick-wall metal tubes, (9) can be written as

$$E_g = 1.4p \tag{10}$$

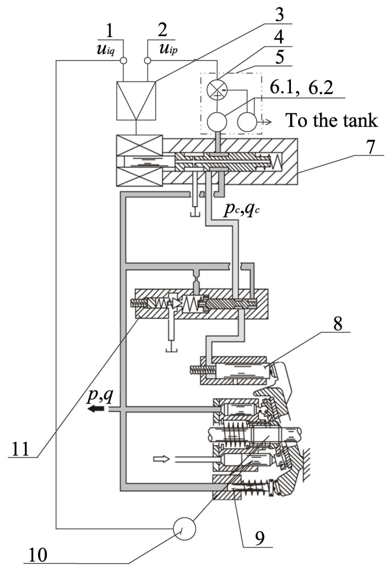
$$E_c = \frac{E_m}{2(1+\gamma)} \tag{11}$$

Through experimental data fitting, bulk modulus of liquid fluid is expressed by ambient pressure and seawater temperature [30].

$$E_l = -0.0001p^2 + 1.2p + 0.1 \cdot \left[1.57 + 0.15 \cdot \log(v_{atm,20°C})\right] \cdot 10^{4+\frac{20-t}{417}} \tag{12}$$

where, $v_{atm,20°C}$ is the kinematic viscosity of fluid under temperature of 20°C and the atmospheric pressure.

Substituting (10), (11) and (12) into (9), the effective bulk modulus is obtained as (13) shown at the bottom of the next page. where, E_e, E_c, E_l, E_g, E_m represent the effective bulk modulus, the bulk modulus of chamber, the bulk modulus of fluid, the bulk modulus of gas, the bulk modulus of metal tube, respectively. γ is Poisson ratio of mental, and χ is gas content.



1. Input signal for flow-rate control 2. Input signal for pressure control 3. Closed-loop amplifier 4. Differential amplifier 5. SPSS 6 Pressure sensors 7. Servo valve 8. Control piston 9. Bias piston 10. Angle sensor 11. Integrated valves (composed of a relief valve and a pressure-compensated valve)

FIGURE 5. System composition and physical control circuits of OEAVP.

3) MODELING OF OEAVP IN SEAWATER ENVIRONMENT

A prototype of OEAVP is developed in Fig. 5 based on the control principles in Fig.3.

The input signal for pressure control 1 or flow-rate 2 is compared with the corresponding feedback, and the error is amplified to drive the servo valve 7 moving, the pressure and flow-rate of the control piston 8 is controlled. As setting up a new equilibrium state with bias piston 9, dynamic regulations of the angle of swash-plate and discharge pressure are accomplished. If discharge pressure reaches the safety pressure, safety valve opens automatically to ensure system safety. In fact, the control process for pressure or flow-rate of the OEAVP works independently, that is, when either system takes effect, another keeps unchanged.

a: MODELING ASSUMPTIONS

Except for electrical components, such as the SPSS and angle sensor are protected through pressure-resistant housings, other elements of OEAVP are all submersed into pressurized fluid environment. Therefore, force equilibrium relationships for these elements like in atmospheric conditions are maintained in ocean. Other modeling assumptions includes:

① Hydraulic fluid is regarded as Newtonian fluid.

② Mechanical components are treated as rigid bodies, such as the spool of valves, pistons, etc.

③ Due to thin-wall and superior heat dissipation of tank, fluid temperature in tank is equal to the local seawater's.

b: SENSING ELEMENTS

Supposed that sensors for measuring pressure and angle are proportional components, the SPSS is employed as a differential amplification, and represented as

$$u_{bp} = k_{dp}k_{bp}\,(p - p_h) = k_{dp}k_{bp}p_r \tag{14}$$

The angle sensor can be written as

$$u_{bq} = k_{bq}\delta \tag{15}$$

where, p, p_r and p_h present the absolute discharge pressure, the relative discharge pressure, and the ambient pressure at given depth h calculated by (3) and (4), respectively. k_{bp}, k_{bq} are sensitive factors of pressure and angle sensors, respectively. k_{dp} is the amplifying ratio of the amplifier. u_{bp}, u_{bq} are feedback signals of pressure and flow-rate, respectively.

c: ELECTRO-HYDRAULIC DRIVE UNIT

Closed-loop amplifier is simplified as a differential and amplifying element, while the electromagnet of valve is viewed as a proportional component.

The output force acting on the spool of valve is indicated respectively as

$$F_{ep} = k_e k_{ip}(u_{ip} - u_{bp}) \tag{16}$$

$$F_{eq} = k_e k_{iq}(u_{iq} - u_{bq}) \tag{17}$$

where, k_{ip}, k_{iq} are proportional factors of input signals for pressure and flow-rate control, respectively. k_e is the gain of electromagnet. u_{ip}, u_{iq} are input signals of pressure and flow-rate. F_{ep}, F_{eq} are the relevant drive force for pressure and flow-rate control, respectively.

d: SERVO VALVE

At a given opening of the spool of valve in Fig.5, the force equilibrium equation is denoted as

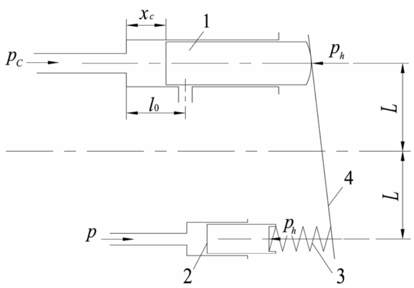
$$F_{ep} + F_{eq} - k_s x_v = m_e\ddot{x}_v + B_{ve}\dot{x}_v + k_{sv}x_v \tag{18}$$

where, k_s, k_{sv} are the spring stiffness and the stiffness of hydraulic spring. x_v is the displacement of spool, m_e is the total mass of the spool and fluid to be pushed. B_e is the viscous damping of the valve, and expressed as [22]

$$B_v = \frac{\pi d_1 l}{\Delta r}\mu \tag{19}$$

where, d_1 is the diameter of moving cylinder, L, Δr are the fitting length and the radial clearance between cylinder and hole, respectively.

$$\frac{1}{E_e} = \frac{1}{E_m/2(1+\gamma)} + \frac{\chi}{1.4p} + \frac{1}{-0.0001p^2 + 1.2p + 0.1\cdot\left[1.57 + 0.15\cdot\log(\nu_{atm,20^\circ C})\right]\cdot 10^{4+\frac{20-t}{417}}} \tag{13}$$



1. Control piston 2. Bias piston 3. Return spring 4. Swash plate

FIGURE 6. **The geometrical scheme of swash plate.**

Though linearizing at the equilibrium point, the flow continuity equation is presented as

$$q_c = k_q x_v - k_c(p - p_c) \tag{20}$$

where, q_c is the flow-rate passing through the valve. k_q, k_c are the gain and flow-pressure coefficients of the valve at a given opening, and p_c is the pressure in control piston.

e: CONTROL PISTON

Neglecting leakage, the moving velocity of control piston is computed as

$$\dot{x}_c = \frac{q_c}{A_c} \tag{21}$$

According to the geometrical position of swash plate in Fig.6, the following kinematic relationship is deduced.

$$\tan\delta = \frac{l_0 - x_c}{L} \tag{22}$$

The dynamic forces equation of swash plate exerted from the control piston and bias piston is written as

$$(p_c - p_h)A_c - k_x x_c - A_x(p - p_h) = m_c\ddot{x}_c + B_c\dot{x}_c \tag{23}$$

where, l_0 is the maximum displacement of control piston, δ is the angle of swash plate. x_c is the displacement at given angle. L is the center distance from the drive shaft to control piston, respectively. A_c, A_x is the area of control piston and the area of bias piston, respectively. k_x is the stiffness of return spring. m_c is the total mass of the control piston and fluid to be pushed. B_c is the viscous damping of control piston, and also can be calculated from (19).

f: OUTLET VOLUME OF OEAVP

Applying flow continuity equations to outlet volume of OEAVP, output flow is represented as

$$q_t \doteq k_Q\delta = \frac{V}{E_e}\dot{p} + \lambda_p(p - p_h) + q_c + q \tag{24}$$

where, $q = \frac{\pi}{4}nzd_0^2D$, n is the rotating speed of pump, z, d_0 are the numbers and the diameter of plunger piston, and D is the distribution diameter of plunger pistons. k_Q is the flow-rate gain of the swash-plate angle. V is the total control volume surrounded by outlet of pump, inlet of hydraulic actuators and entrance of control valve. E_e is the effective bulk modulus of fluid, expressed in (13). λ_p is the leaking factor of OEAVP. q_c, q_t and q are the flow-rate entering into control piston, the theoretical flow-rate and the actual flow-rate to the pump, respectively.

B. ANALYSIS OF CONTROL CHARACTERISTICS

When control characteristics of pressure or flow-rate are settled, the control system of OEAVP would run in a relative steady state. At this moment, increments of above-mentioned variables satisfy $\dot{x}_c = 0, \ddot{x}_c = 0, \dot{x}_v = 0$ and $\dot{p} = 0$. In addition, since angle changes of swash plate is small, the equation $\tan\delta \approx \delta$ is often established.

Combining equations (14) $\sim$ (23), a coupling characteristic equation presenting the controls of pressure and angle of OEAVP with input signals is written as

$$k_{ip}(u_{ip} - k_{dq}k_{bq}(p - p_h)) + k_{iq}(u_{iq} - k_{bq}\delta) = a\cdot(p - p_h) + b\cdot\delta + c \tag{25}$$

where, $a = \frac{k_c(k_s+k_{sv})(A_c-A_x)}{k_ek_qA_c}$, $b = \frac{k_ck_x(k_s+k_{sv})L}{k_ek_qA_c}$, $c = -\frac{k_ck_xl_0(k_s+k_{sv})}{k_ek_qA_c}$. Factors a, b and c denote the compound relations among stiffness, gain and structure sizes. They meet $\frac{b}{a} = \frac{A_c-A_x}{L}$, and $\frac{c}{b} = -\frac{l_0}{L}$.

Case 1 (Pressure Control Characteristics): If the pressure control works of OEAVP, following equations are established.

$$\begin{cases} p_r = p - p_h \\ u_{iq} - k_{bq}\delta = 0 \end{cases} \tag{26}$$

Substituting into (25), characteristic equation for pressure control is simplified as

$$p_r = \frac{k_{ip}}{k_{ip}k_{dp}k_{bp} + a}u_{ip} - \frac{b\delta + c}{k_{ip}k_{dp}k_{bp} + a} \tag{27}$$

For the pressure control, u_{ip} and δ are constant at specific condition. Obviously, the discharge pressure p_r is proportional to its input signal u_{ip}, and is not affected by seawater pressure, which behaves a good adaptability in variable oceanographic environment. The second item displays a dead-zone existence. Moreover, increasing angle δ will cause largening dead-zone.

Case 2 (Flow-Rate Control Characteristics): Similarly, substituting $u_{ip} - k_{dq}k_{bq}(p - p_h) = 0$ into (25), characteristic equation for variable displacement control is derived as

$$\delta = \frac{k_{iq}}{k_{iq}k_{bq} + b}u_{iq} - \frac{ap_r + c}{k_{iq}k_{bq} + b} \tag{28}$$

Substituting (28) into (24), and neglecting the leaking flow-rate and the control flow-rate q_c, the characteristic equation for flow-rate control is simplified as

$$q = q_t = \frac{k_Qk_{iq}}{k_{iq}k_{bq} + b}u_{iq} - \frac{k_Q(ap_r + c)}{k_{iq}k_{bq} + b} \tag{29}$$

For the flow-rate control, u_{iq} and p_r keep constants at a given condition. The output flow-rate q changes linearly with its input signal u_{iq}, and also not impacted from ambient pressure. In second item, a dead zone appears, and expands with the increase of discharge pressure p_r.

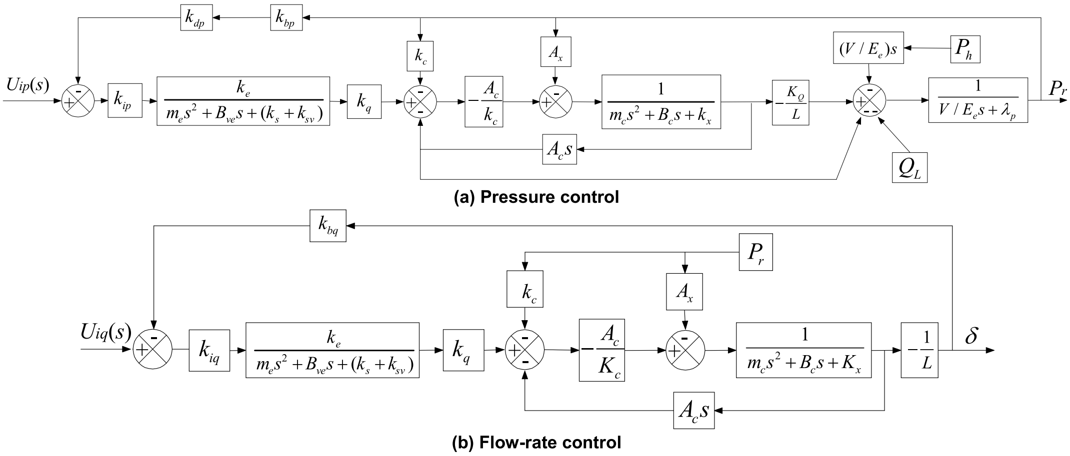


FIGURE 7. Control system block scheme of OEAVP in oceanographic environment.

C. ANALYSIS OF SYSTEM STABILITY

Considering properties changes of hydraulic fluid in variable oceanographic environment, the stability of control system of OEAVP with variances of viscous damping and fluid compressibility should be analyzed. Based on environmental model (6) and fluid model (7) and (13), then combining (14) $\sim$ (24) and carrying out Laplace transform to obtain dynamic control models for pressure and flow-rate of OEAVP in ocean, shown in Fig.7.

From Fig.7(a), pressure control scheme of OEAVP is a negative closed-loop control system with P controller k_{ip}. Seawater environmental parameters influence on control frame through two manners. One is direct effects from ambient pressure P_h, another is indirect effects from internal parameters variances of control system related with hydraulic fluid, such as viscous damping B_{ve}, B_c seen as (19), effective bulk modulus shown in (13), etc., which are caused by the changes of fluid stiffness and viscosity in oceanographic environment.

From Fig.7(b), the flow-rate control scheme of OEAVP is also a negative closed-loop control system with P controller k_{iq}. The mechanism of environmental effect on control frame is relatively simple, only including indirect effects.

The parameters of OEAVP are listed according to the components in Fig.5, whose values are shown in TABLE 1.

Selecting ISO VG32 as hydraulic fluid of the system and substituting parameters in Table 1 into the block scheme in Fig.7, MATLAB/Simulink tool is adopted to analyze the stabilities of OEAVP system, and the bode diagrams of pressure and flow-rate controls at sea level, at the depth of 1500m and at 3000m in deep-sea are plotted in Fig.8, respectively.

In Fig.8(a), with the ocean-depth increasing from 0 (at sea level) to 3000m, the amplitude margin of pressure control increases from 11.6dB,17.7dB to 19.4dB. The amplitude margin only raising 1.7dB in deep-sea range from 1500m to 3000m is much less than 6.1dB in shallow-water range from 0 to 1500m. The phase margin enlarges from 83.1°C,110.8°C to 122.9°C, and the increment 27.7°C in shallow-water range is larger than 12.1°C in deep-sea range. Both margins

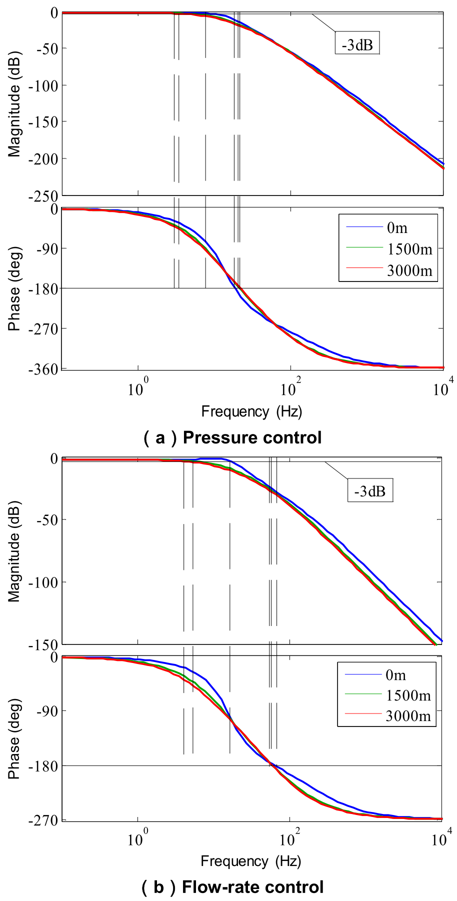


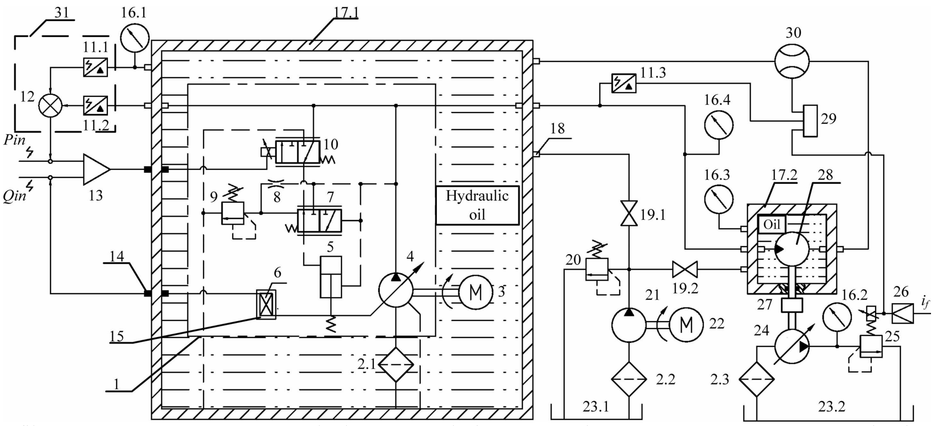
FIGURE 8. Bode diagrams of pressure/flow-rate control system in different depth.

conform to the stability requirements of engineering control system [31].

The stability of pressure control become strong in oceanographic environment, meanwhile the growth of stability gets slow when exceeding 1500m. This is because the viscosity and the bulk modulus of hydraulic fluid greatly affects

TABLE 1. Parameters values of OEAVP.

Coefficient	Value	Unit	Components	Coefficient	Values	Unit	Components
m_e	0.021	kg		m_c	0.231	kg	
k_e	64.4	N/A		d_c	0.024	m	
d_e	0.008	m	Control valve	l_{fc}	0.056	m	Control piston
l_{fe}	0.024	m		Δr_c	2.5×10^{-5}	m	
Δr_e	8×10^{-6}	m		l_0	0.021	m	
k_s	8620	N/m		k_Q	1.8×10^{-5}	m^3/s/rad	Pump body
k_{sv}	4325	N/m		k_x	1850	N/m	
k_q	0.566	m^2/s		L	0.074	m	
k_c	1.31×10^{-8}	m^3/s/Pa		V	2.5×10^{-3}	m^3	
K	0.01456	mPa·s		λ_p	9.5×10^{-11}	m^3/s/Pa	
B	1711.9	°C		k_{bp}	8.3×10^{-7}	V/Pa	
C	182.7	°C		k_{dp}	1.14		
a_1	71.74	MPa		k_{bq}	6.45	V/rad	Amplifiers and sensors
a_2	0.4453	MPa/°C	Hydraulic fluid	k_{ip}	3.64	A/V	
b_1	0.01532			k_{iq}	2.38	A/V	
b_2	3.17×10^{-4}	$°C^{-1}$					
$\nu_{atm,20°C}$	56.8	cSt					
E_c	1.9×10^5	MPa					
E_l	1500	MPa					



1. OEAVP 2. Hydraulic filter 3. Deep-sea motor 4. Pump body 5. Control piston 6. Angle sensor 7.Pressure-compensated valve 8.Orifice 9.Safty valve 10.Electro-hydraulic proportional valve 11.Pressure sensors 12.Differential amplifier 13.Closed-loop amplifier 14.Electrical interfaces 15.Pressure-resistant shell 16.Pressure gauges 17.Deep-sea simulation hulls 18.Hydraulic joints 19.On-off valves 20.Relief valve 21.High-pressure pump 22.Electric motor 23.Fluid reservoir 24.Pump 25.Loading valve 26. Load amplifier 27. Coupling 28. Motor 29. Computer 30. Flow-rate meter 31. SPSS

FIGURE 9. Testing principles of the OEAVP in deep-sea simulation hull.

the stability of system. From the curves of environmental models in Fig.4, the ambient pressure is proportional to changes of ocean-depth, while ambient temperature has a steeply decline from 28°C at sea level to 3°C at 1500m, and then descends slowly to 1°C at 3000m. The compound effects from temperature declining and pressure increasing will prompt the fluid viscosity and the system damping significantly increases, which results to the system stability to vary quickly in shallow-water and gradually in deep-sea.

From Fig.8(b), with ocean-depth deepening, the amplitude margin of flow-rate control of OEAVP presents small risings from 24.1dB,27.6dB to 29.4dB. The phase margin displays an increase from 76°C,137.3°C to 144°C. Similarly, system stability of flow-rate control changes rapidly in shallow-water and smoothly in deep-sea. Both margins also accord with the stability demands, while extra margins especially for phase margin will slow down the dynamic response.

IV. PERFORMANCE EXPERIMENTS OF OEAVP IN DEEP-SEA SIMULATION HULL

A. TESTBEDS SET-UP

Testing hydraulic schematic of OEAVP in deep-sea simulation hull and its physical devices is shown in Fig.9 and Fig.10. The tested SPSS and the OEAVP are shown in the left bottom and right corner in Fig.10. This testing system can be divided into a testing circuit for OEAVP, environment simulating systems, and data monitoring devices. The testing circuit is consisted of the tested SPSS 31, the OEAVP 1 including elements 4-13 (specific composition see in Fig.5), a deep-sea motor 3,a hydraulic motor 28, and their loading circuit made up of a coupling 27, a pump 24, a loading valve 25, its load amplifier 26 and fluid reservoir 23.2. Setting different signals i_f in 26 impose torque loads for the motor 28. The environment simulating systems are designed to simulate oceanographic high-pressure surroundings for test elements 1 and 28, constituted of two fluid-filled deep-sea

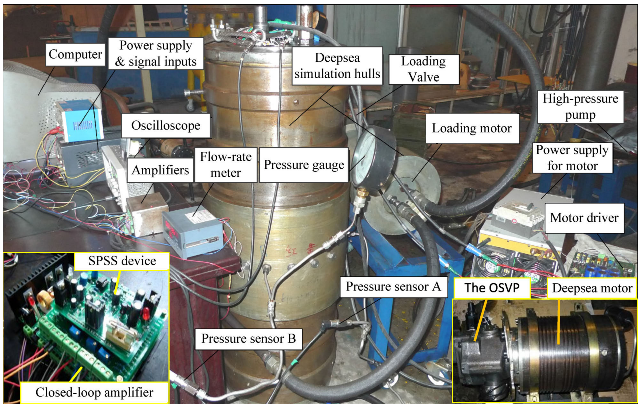


FIGURE 10. Experimental devices for SPSS and OEAVP.

simulation hulls 17.1 and 17.2, and a high-pressure pressurizing circuit involving a high-pressure pump 21, an electric motor 22, a relief valve 20, and auxiliary elements 19 and 23.1. Opening the valves 19.1 and 19.2 and tuning the valve 20 can set variable environmental pressure. The data monitoring devices contains pressure sensors 11, a flow-rate meter 30, a computer 29 to collect signals and pressure gauges 16.

B. SPSS PERFORMACES TESTING

To simulate oceanographic environments at sea level, at 1500m and at 3000m deep-sea, hulls 17 are pressurized by the valve 20 with 0.1MPa, 15MPa and 30MPa, respectively. The input signal of flow-rate is given as $Q_{in} = 5$V and the input signal of pressure P_{in} is set as a triangular wave with amplitude 0∼3V and frequency 0.2Hz. Signals of discharge pressure P_A of OEAVP, hull pressure (ambient pressure) P_B and relative pressure P_r by *SPSS* 31 are measured as shown in Fig.11.

From Fig.11(2), after a short distortion, discharge pressure of OEAVP (expressed by absolute pressure) can well track the input triangular pressure P_{in} except for the inflection regions. With the increasing of hull pressure shown in Fig.11(1), the distortion region become narrower from 4.5s at 0.1MPa to 4.2s at 30MPa, and the mean change of the curves is improved, seen the white lines in Fig.11(2). The relative pressure P_r in Fig.11 (3) represents the output of SPSS, it tracks the input pressure very well in different hull pressure, presents the SPSS with excellent adaptabilities to variable ocean depth and well matches with the closed-loop amplifier of OEAVP, which verifies that the SPSS and the pressure control principle are reasonable and effective for OEAVP in oceanographic environment,

C. CONTROL CHARACTERISTICS PERFORMACES TESTING

To simulate at sea level and at 3000m deep-sea environments, hulls 17 are pressurized as 0.1MPa and 30MPa, respectively. The input signal of flow-rate is set as $Q_{in} = 5$V and the input of pressure P_{in} varies from 0∼5V. Relative output pressure p_r of OEAVP is as plotted in Fig.12(1). Similarly, keeping

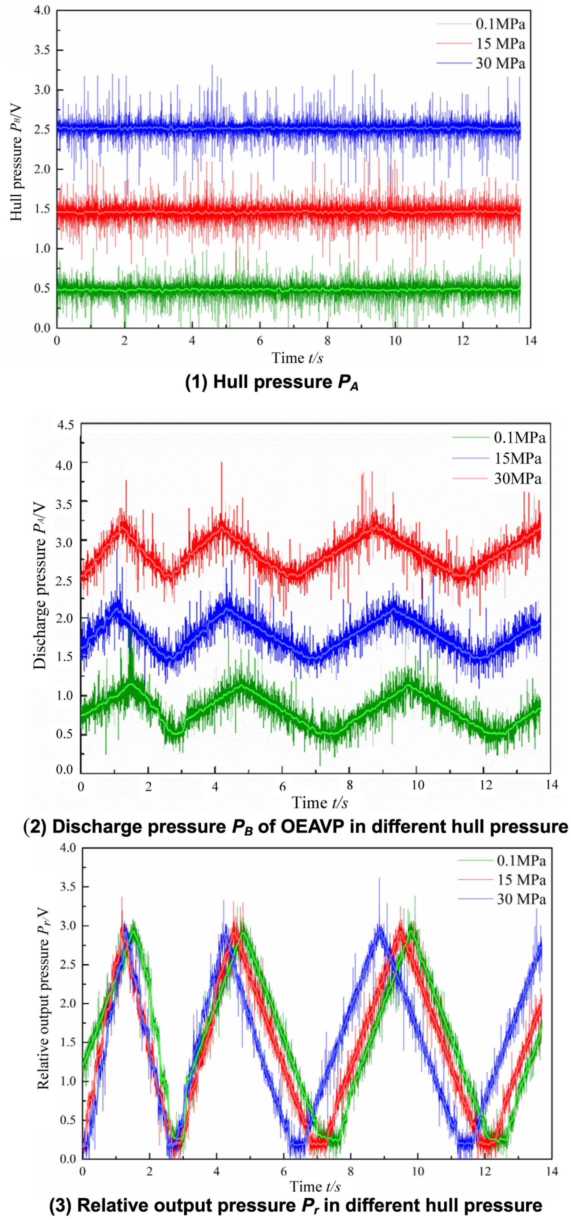


FIGURE 11. Discharge pressure and relative output pressure of OEAVP vary with different hull pressure.

the input signal of pressure $P_{in} = 5$V and varying the input of flow-rate Q_{in} from 0∼5V, output flow-rate of OEAVP is shown in Fig.12(2).

From Fig.12 (1), the dead zone expands from 0.2V in 0.1MPa to 0.5V in 30MPa. After crossing the zone, both curves are approximately parallel, having the same linearity, which is consistent with the characteristic equation (27). When the input signal reaches the rated voltage $P_{in} = 5$V, the relative discharge pressure is 16.2MPa and 15.8MPa, respectively, and declines 3.7% in 30MPa compared with in 0. 1MPa. Obviously, the proportional characteristics of pressure

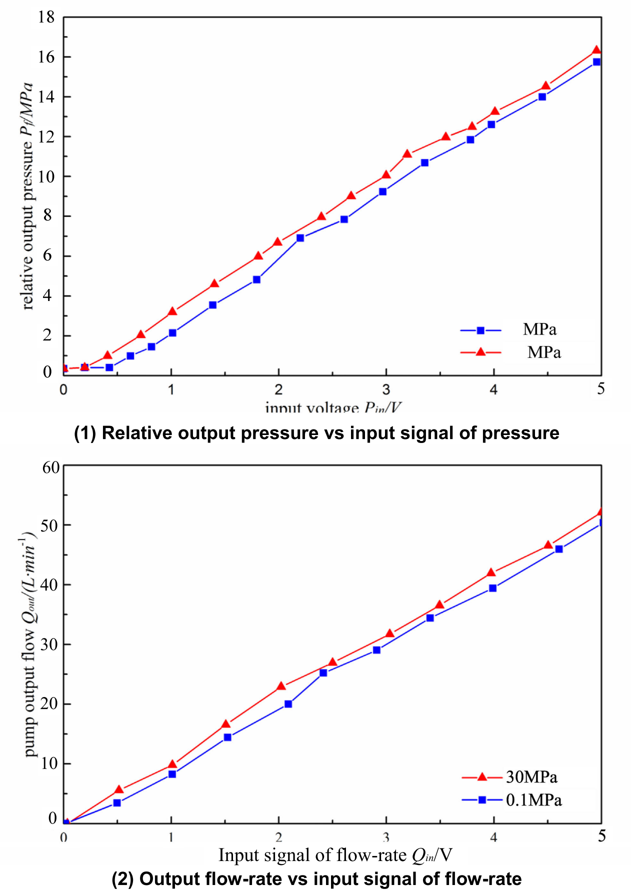


FIGURE 12. Control characteristics curves of pressure and flow-rate of OEAVP in different hull pressure.

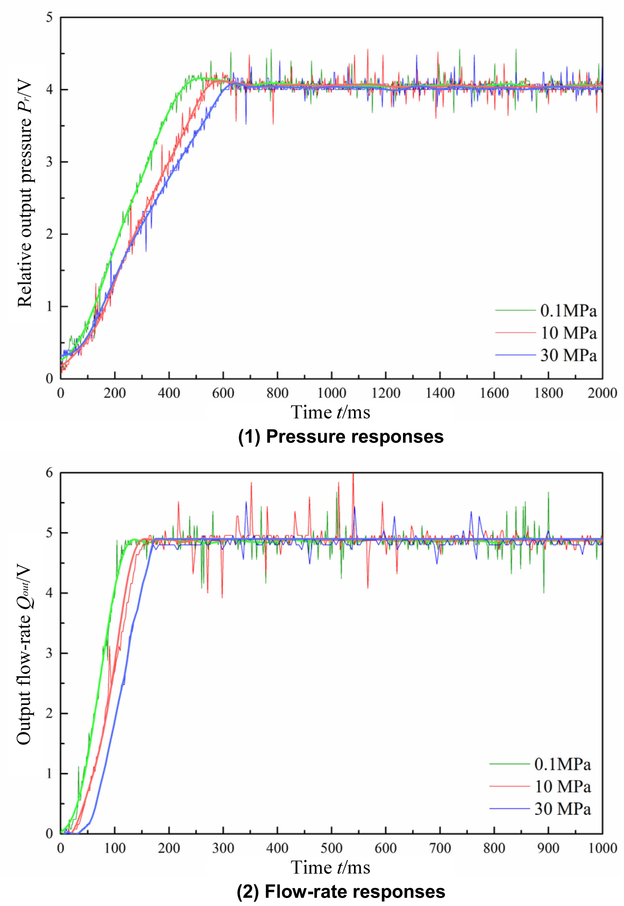


FIGURE 13. Dynamic responses of pressure and flow-rate control systems in different hull pressures.

control of the OEAVP are well maintained in different ocean-depth.

From Fig.12 (2), the dead zone of flow-rate control also expands in higher pressure 30MPa, and both curves have good linearities. When the control signal Q_{in} keeps the same value, the output flow-rate decreases slightly with hull pressure increasing. At the rated voltage $Q_{in} = 5$V, the relative output flow-rate is 52.3L/min and 50L/min, respectively, and deceases 4.4%, this shows that the changes strongly agree with the flow-rate characteristic in equation (29).

These good control characteristics of pressure and flow-rate also verify that the self-adapted sensing methods adopted in closed-loop feedback lines and the control principles of OEAVP can run smoothly and effectively in oceanographic environment.

D. RESPONSES TESTING

1) PRESSURE RESPONSES

To simulate oceanographic environments at sea level, at 1500m and at 3000m deep-sea, hulls 17 are pressurized with 0.1MPa, 15MPa and 30MPa, respectively. The input signal of flow-rate is set as $Q_{in} = 5$V, and the input of pressure P_{in} is given as a step signal from 0V to 4V. Pressure responses of OEAVP are shown in Fig.13 (1).

From Fig.13(1), with hull pressure increasing from 0.1MPa to 30MPa, the steady-state value of pressure response has a slight drop from 3.9V to 3.78V, the overshoot decreases and system stability becomes strong, which are consistent with analysis results of system stability. The rise time raises from 420ms at 0.1MPa to 680ms at 30MPa, representing that dynamic response slows down. Considering the viscosity-pressure relationship of hydraulic fluid (7) and environmental models (6), the increasing of fluid viscosity with ambient pressure results in an augment of viscous system, which promotes the dynamic damping of system as it is approaching to an overdamping status, manifests as dynamic response decreased and the stability of system is improved.

The parameters setting for flow-rate responses test are the same as for pressure responses. The input signal of flow P_{in} is given as $P_{in} = 5$V, and the input of pressure Q_{in} is set as a step signal from 0V to 5V. Flow-rate responses of OEAVP are shown in Fig.13(2).

From Fig.13(2), with hull pressure increasing from 0.1MPa to 30MPa, the flow-rate response also has a slight drop with steady-state value from 4.92V to 4.8V, and rise time from 180ms to 230ms. These changes are similar as for the pressure responses, while the response time is shorter. Because the process of flow-rate control is simpler than the pressure control's and its feedback line is the same as in the land-used condition, it is only affected by indirect effects seen section 3.3.

V. CONCLUSION

In this paper, the goals dedicated to develop an oceanographic environment adaptive variable pumps (OEAVP) and systematically analyze its performances in deep-sea applications.

(1) A novel close-loop control structures of variable pumps for deep-sea application is proposed to autonomously adapt to variable oceanographic environment. The self-adaptive pressure sensing scheme (SPSS) and the flow-rate pressure-resistant sensing method are designed to achieve adaptive measurement of hydraulic variables for closed-loop control system in ocean.

(2) Based on environmental models and fluid models, characteristics equations, and dynamic control models of pressure and flow-rate control for OEAVP in ocean are derived. Analysis of control characteristics shows the control output regardless to the discharge pressure or the output flow-rate, is proportional to the input signal except for dead-zones, not affected from seawater pressure, and has good adaptabilities in variable oceanographic environment. Analysis of system stability demonstrates margins of the system increase whereas fast responses slow down with the increasing of depths, which changes significantly especially in shallow-water from 0 to 1500m. It reveals oceanographic environment influences on control performances of OEAVP from direct effect by ambient pressure and indirect effect by properties changes of hydraulic fluid.

(3) Experimental tests on performances of OEAVP in deep-sea simulation hull are performed. The SPSS performances testing shows the output can track the input pressure very well after a short distortion in no more than 4.5s in 30MPa, and has excellent adaptabilities in variable ocean-depth. The control characteristics testing presents the proportional characteristics of pressure or flow-rate control of OEAVP as well maintained, while the rated value slightly decreases and the dead zone gradually expands with the increasing of ocean-depth, which are well consistent with the theoretical results. Dynamic responses testing displays the steady-state value with a slight drop, while the overshoot decreases and system stability becomes strong, which verify system damping increasing with the ocean-depth deepening and are identical with the results of steady-state analysis of dynamic control models.

(4) Seawater temperature is difficult to control at the confined environment of the simulation hull, so the testing about influences of seawater temperature on the performances of OEAVP should be made with more efforts in future study.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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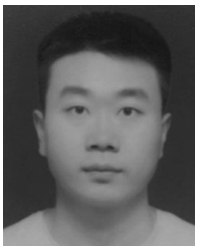

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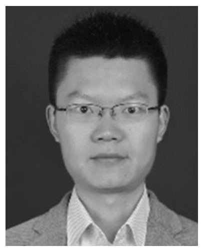

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