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A 6-DOF Deep-ocean Mining Ship Motion Simulator

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Abstract: In order to build up a simulation test installation of mechanical behavior of the lifting pipe system which is the key component of deep-ocean mining system, a mining ship motion simulator is developed. The Stewart 6-DOF platform is selected to simulate the 6-DOF motions including pitch, roll, yaw, surge, sway and heave. According to mining ship response and similarity principles, the pitch, roll, yaw angles are less than 20 degrees and surge, sway, heave amplitudes are less than 200 mm. The upper and bottom platform are connected by six hydraulic cylinders which are driven by six electro-hydraulic proportional valves independently. PID control and fuzzy PID control were chosen as the control strategy. The fuzzy PID control outweighs the PID control. The test results show that the mining ship motion simulator can move under the predetermined attitude and can be used as a mining ship simulator.

Key words: Mining ship motion simulator, 6-DOF platform, Direct and reverse solve, fuzzy PID control

INTRODUCTION

A typical and may be the most prospective deep-ocean mining system is an integration of self-propelled seafloor miner, miner-to-buffer flexible hose, buffer, pumps, lift pipe, mining ship and ocean transportation system. The nodules collected by the miner are lifted by the fluid rising force through the lifting pipeline to the mining ship (Liu *et al*., 2003). As the lifting pipe is thousands of meters long, it is influenced by the motion of the mining ship, the motion of the miner, ocean environment loads, the motion of the slurry inside the pipe and so on. The mechanical behavior of the lifting pipe which determines the efficiency and viability of the system is of key importance. Therefore, the analysis of the mechanical behavior is the research focus since the very beginning of the development of deep-ocean mining technology (Xu *et al*., 2007; Feng *et al*., 2007). In order to build up a simulation test installation of mechanical behavior of the lifting pipe system, a mining ship motion simulator need to be developed.

At present, various ship motion simulators are developed by companies and research institutes. National Biodynamic Laboratory of USA developed a 3-DOF Ship Motion Simulator (SMS) to carry out the research of staff working abilities under various sea conditions and medicine efficacy of motion sickness. The weight capacity is 1800 kg including the test bin and three people and it could simulate the fifth level sea condition. SPAWAR Center of USA also developed a 3-DOF SMS to test the performance of instruments. A 2-DOF (pitch and roll) SMS was developed by USA Naval Surface Warfare Center's Indian SPAWAR Head Division. And it could simulate the seventh level sea condition. The Netherlands Organization for Applied Scientific Research (TNO) designed a 3-DOF SMS with the capacity of 4m*2.4m*2.3m. The pitch angle is less than 40 degrees and the roll angle is less than 30 degrees. Its heave amplitude is less than 1 m. It is also used to do a study on motion sickness. A 6-DOF SMS designed by August Design Company of USA is used to train staff and test instruments.

With the advantages of simple structure, high stiffness, high accuracy and high load capacity, the Stewart 6-DOF platform is extensively used in flight simulator, vehicle simulator, sea wave simulator, multi-degree of freedom swaying platform and so on (Yang, 2002 and Yang *et al*., 2003). Here, the Stewart 6-DOF platform is chosen to simulate the motion of the mining ship with the aim of setting up a simulation test installation of mechanical behavior of the lifting pipe system.

SHIP MOTION SIMULATOR DESIGN

There are six motions of mining ship: pitch, roll, yaw, surge, sway and heave. Yaw, surge and sway can be

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Table 1: Ship response at sea trial site

Sea condition	Level 4	Level 6
Pitch amplitude (°)	2.00	7.5
Pitch period (s)	5.80	8.8
Roll ampltude (°)	2.00	11.0
Roll period (s)	11.60	17.6
Heave amplitude (m)	0.36	0.9
Heave period (s)	5.80	8.8

Table 2: Parameters of mining ship motion simulator

Diameter of upper platform	1.2 m
Diameter of lower platform	1.6 m
Total length of hydraulic cylinder	1.5 m
Piston area of hydraulic cylinder (rear end)	$2.313*10^{-3}m^{-2}$
Operating pressure	7 MPa
Rated pressure	16 MPa
Working stroke	0.5 m
Rated flow	120 L min^{-1}
Operating flow	80 L min^{-1}
Motor capacity	37 kW
Motor speed	1480 r min^{-1}
Accumulator volume	4 L

Fig. 1: Photo of 6-DOF platform

eliminated by ship dynamic positioning. Therefore, pitch, roll and heave compensation is considered here. Table 1 gives out the ship response at sea trial site. Based on similar principles, the pitch and roll angle is less than 20 degrees and heave amplitude is less than 200 mm. The motions of pitch, roll, heave motion and their combinations could be realized (Huang *et al*., 1997; Xiao *et al*., 2004).

The Stewart platform is designed and built to simulate the mining ship motion as shown in Fig.1. The upper and bottom platform are connected by six hydraulic cylinders which are driven by six electro-hydraulic proportional valves independently (Han and Jiang, 2011). The main parameters of the platform are shown in Table 2.

The 6-DOF platform can be divided into hydraulic system and control system. The hydraulic system shown in Fig. 2 is composed of hydraulic cylinders, electro-hydraulic proportional valves, hydraulic accumulators and a hydraulic station. The motions of hydraulic cylinders are controlled by electro-hydraulic proportional valves. Two hydraulic cylinders share one accumulator. To ensure the constant oil working pressure, a variable displacement pump is chosen. Therefore, the oil pressure is nearly constant to make sure that the same control voltage means reproducibly the same velocity of hydraulic cylinder.

The core of the control system is an Opto22 SNAP-PAC-S1 programmable automation controller. It provides powerful real-time control and communications to meet industrial control, monitoring and data acquisition needs. The input and output modules are all Opto products. Displacement of hydraulic cylinders, oil pressure and temperature signals are sampled by analog input modules. Analog output modules give out control voltages to control the flow and direction of electro-hydraulic proportional valves.

DIRECT AND REVERSE SOLVE OF 6-DOF PLATFORM

In order to realize closed loop control of the platform, direct and reverse solve must be solved (Zhang *et al*., 2003). Direct solve is to solve platform attitude according to the six lengths of hydraulic cylinders, reverse solve is just the contrary calculation.

As shown in the Fig. 3, the six upper hinge joints A_i (i = 1, 2, 3, 4, 5, 6) are located at the radius r_a. The six underside hinge joints B_i (I = 1, 2, 3, 4, 5, 6) are located at the radius r_b. The circle center of upper circumference is selected as coordinate origin. The coordinate OXYZ is fixed on the upper platform and static coordinate O'X'Y'Z' is on the underside platform. The initial height (the vertical height between upper and underside hinge joints) of moving platform is h.

Form the geometric relation of Fig. 3, the coordinates of upper and underside hinge joints are given below:

$$A=\begin{bmatrix} r_a\cos\omega_a & -r_a\sin(30-\omega_a) & -r_a\cos(60-\omega_a) & -r_a\cos(60-\omega_a) & -r_a\sin(30-\omega_a) & r_a\cos\omega_a \\ -r_a\sin\omega_a & -r_a\cos(30-\omega_a) & -r_a\sin(60-\omega_a) & r_a\sin(60-\omega_a) & r_a\cos(30-\omega_a) & r_a\sin\omega_a \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (1)$$

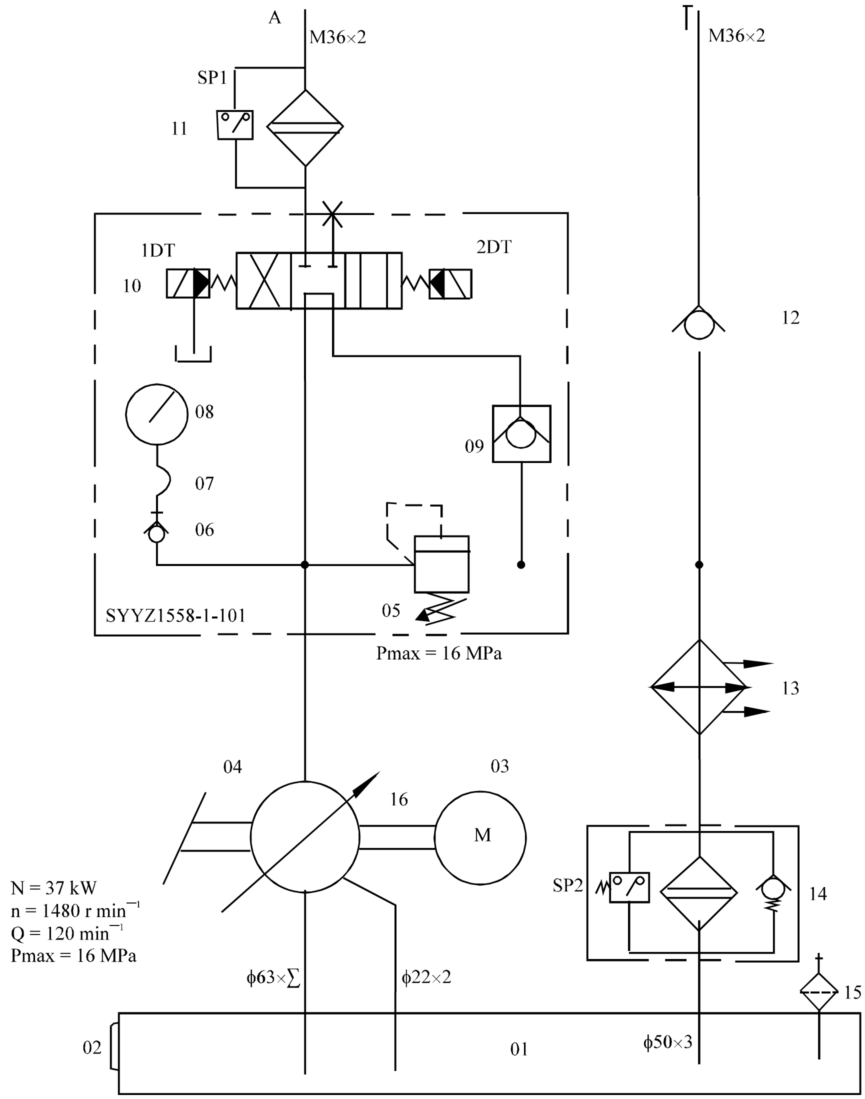

Fig. 2: Hydraulic system diagram of 6-DOF platform

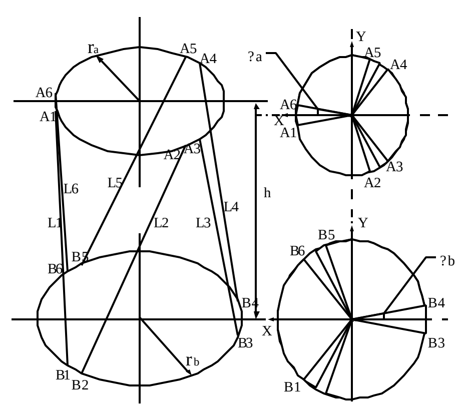

Fig. 3: Structural diagram of 6-DOF platform

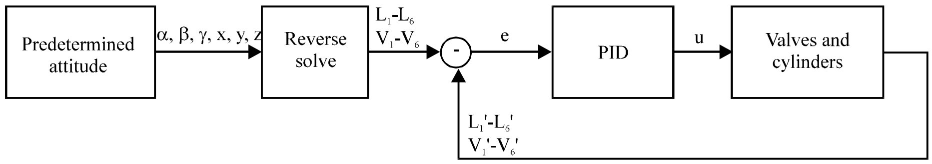

Fig. 4: PID control of 6-DOF platform

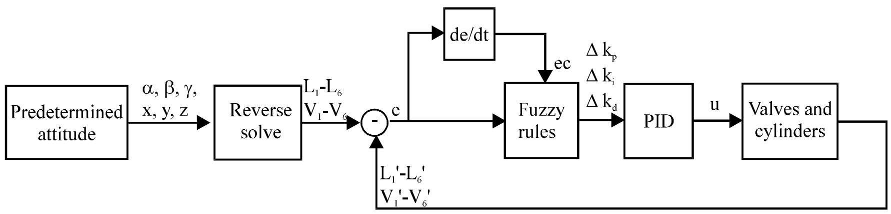

Fig. 5 Fuzzy PID control of 6-DOF platform

$$B=\begin{bmatrix} r_b\cos(60-\omega_b) & r_b\sin(30-\omega_b) & -r_b\cos\omega_b & -r_b\cos\omega_b & r_b\sin(30-\omega_b) & r_b\cos(60-\omega_b) \\ -r_b\sin(60-\omega_b) & -r_b\cos(30-\omega_b) & -r_b\sin\omega_b & r_b\sin\omega_b & r_b\cos(30-\omega_b) & r_b\sin(60-\omega_b) \\ h & h & h & h & h & h \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (2)$$

When the attitude of the moving platform is $Q=(\alpha,\beta,\gamma,x_p,y_p,z_p)$, the transformation matrix is given by:

$$R=\begin{bmatrix} c\beta c\gamma & -c\alpha s\gamma+s\alpha s\beta c\gamma & s\alpha s\gamma+c\alpha s\beta c\gamma & x_p \\ c\beta s\gamma & c\alpha c\gamma+s\alpha s\beta s\gamma & -s\alpha c\gamma+c\alpha s\beta s\gamma & y_p \\ c\beta c\gamma & s\alpha c\beta & c\alpha c\beta & z_p \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where, α is roll, β is pitch, γ is yaw, x_p is along O′X′, y_p is along O′Y′, z_p is along O′Z′. c means cos, s means sin. For example,sαc β means sin α cos β.

Thus, the coordinate of upper hinge joints in static coordinate are given below:

$$P = R.A \quad (4)$$

Then reverse solve is obtained and the lengths of hydraulic cylinders can be given by:

$$L_i=\sqrt{\sum_{k=1}^{3}(P_{ki}-B_{ki})^2}\,(i=1,2,3,4,5,6) \quad (5)$$

To realize direct solve, nonlinear equations are bulit:

$$f_i=\sum_{k=1}^{3}(P_{ki}-B_{ki})^2-L_i^2(i=1,2,3,4,5,6) \quad (6)$$

CONTROL STRATEGY AND EXPERIMENTS

First, PID control is selected to control the hydraulic cylinders. Velocity control and displacement control of hydraulic cylinders are tested. The physical model test results indicate that velocity PID control is much better than displacement control. Although the control effects are almost the same, the output control voltage of the electro-hydraulic proportional directional valves in velocity control is much more smooth comparing with the control voltage jump in displacement control.

The aim is to control the displacement of six hydraulic cylinders. The PID control diagram is shown in Fig. 4. First, the displacement of every cylinder at every step is calculated according to the predetermined platform attitude. Secondly, the displacement of next step is calculated based on the displacement of previous step. Therefore, the velocity and direction of every cylinder is obtained. At last, the control voltages are given out according to the velocity-voltage curves of six hydraulic cylinders. In every step, velocity PID control is used. That is to say, the six cylinders move at the uniform speed in every step and the actual speed is close to the calculated speed.

In the test, the pitch and roll amplitude are set to 15 degree and heave amplitude is 75 mm. The displacement of every hydraulic cylinder is recorded and the practical

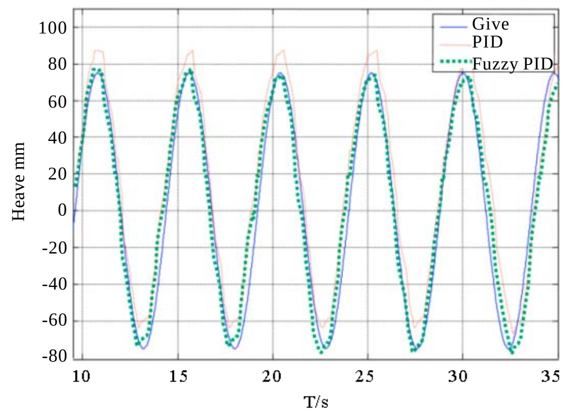

Fig. 6: 1-DOF of heave motion, 5.8 s period and 75 mm amplitude

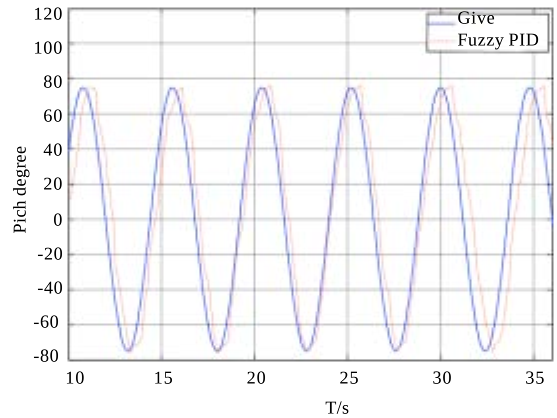

Fig. 9: 3-DOF motion, 5.8 s period and 75 mm amplitude heave motion

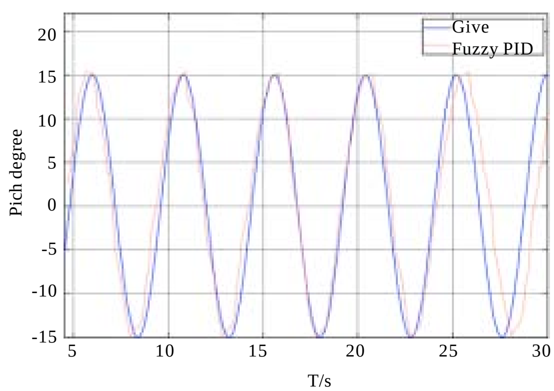

Fig. 7: 1-DOF of pitch motion, 5.8 s period and 15 deg amplitude

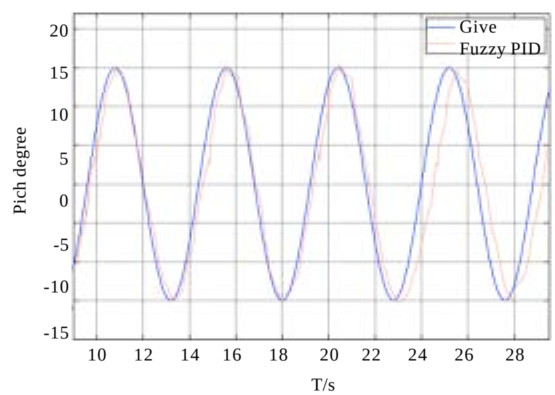

Fig. 10: 3-DOF motion, 5.8 s period and 15 deg amplitude pitch motion

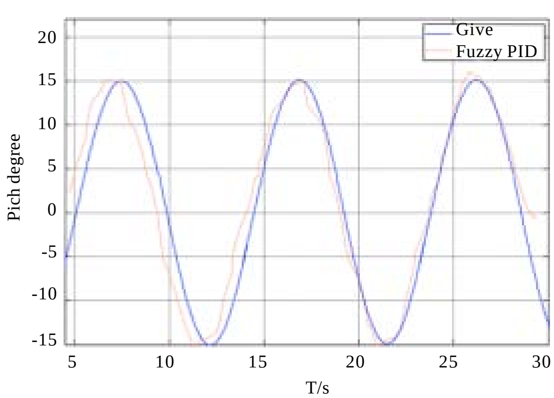

Fig. 8: 1-DOF of roll motion, 11.6 s period and 15 deg amplitude

platform attitude can be solved through direct solve. The result (red line) is shown in Fig. 6. Because of the unsymmetrical cylinders, the fixed PID parameters are resulted in unsymmetrical motions the upper platform. Therefore, fuzzy PID control shown in Fig. 5 is proposed. The PID parameters are adjusted by the velocity error and its rate of change. The test result (green line) is shown is Fig.6. It indicates that the fuzzy PID control prevent the upper platform from moving asymmetrically. The fuzzy PID control is selected to replace the PID control.

The one degree of freedom tests and the three degree of freedom tests were carried out. The pitch and roll amplitudes are set to 15 degree and heave amplitude is 75 mm. Figure 7 and 8 show the results of pitch and roll motion of 1-DOF, respectively. Figure 9, 10 and 11 show the results of heave, pitch and roll motion of 3-DOF, respectively. The platform is able to perform the predetermined attitude path can meet the requirements of the mining ship motions. The figures also show control errors. There are two main reasons: firstly, to simplify the

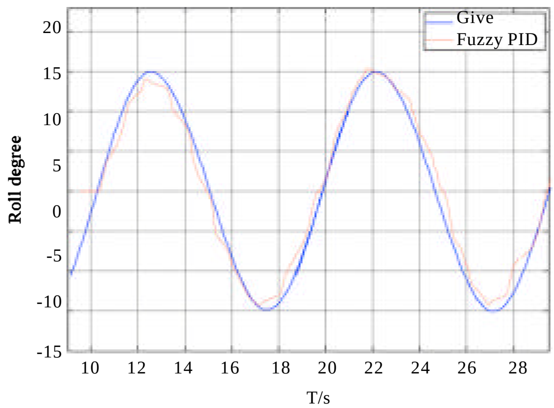

Fig. 11: 3-DOF motion, 11.6 s period and 15 deg amplitude roll motion

math model of 6-DOF platform, the cross hinge is simplified as one point. Secondly, only velocity PID control is realized but attitude closed loop control is not realized.

CONCLUSION

A Stewart 6-DOF platform is built up to simulate the motion of the deep-ocean mining ship. The test results indicate that the fuzzy PID control is better than PID control. The platform is able to perform smoothly under the predetermined attitude path and can meet the requirements of the mining ship motions. The control errors exist and the next step is to realize the closed loop control of the attitudes instead of velocity control of the cylinders.

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