PAPER

Analysis and Research on Mobile Drilling Rig for Deep Seabed Shallow Strata

AUTHORS

Ziqiang Ren
Ocean College, Zhejiang University; and Hainan Institute of Zhejiang University

Feng Zhou
State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University

Hai Zhu
Peihao Zhang
Ocean College, Zhejiang University

Jiawang Chen
Hainan Institute of Zhejiang University; Ocean College, Zhejiang University; Southern Marine Science and Engineering Guangdong Laboratory, Guangzhou, China

Peng Zhou
Ocean College, Zhejiang University

Lieyu Tian
Guangzhou Marine Geological Survey, Guangzhou, China

Chunhu Liu
Xiaochao Zhang
School of Oceanography, Shanghai Jiaotong University

ABSTRACT

Drilling rigs for deep seabed shallow strata are commonly used to explore ocean cobalt-rich crust resources and other fields. This paper mainly presents the structure and mechanism of a mobile drilling rig for use in acquiring seafloor cores that are up to 1.5 m in length. The software Simcenter Amesim is used to establish the mobile drilling rig's hydraulic propulsion system model, which is the basis and a core part of the rig. Moreover, closed-loop and PID (proportion-integral-differential) control methods are separately used to control the hydraulic propulsion system for simulation analysis. Comparison of the simulation results shows that the PID control method is more convincing in verifying the design rationality of the hydraulic propulsion system. In the simulation of the PID-controlled hydraulic propulsion system, the co-simulation technology of Simcenter Amesim and MATLAB/Simulink not only establishes the hydraulic and control models but also determines the relevant simulation parameters, thereby helping improve system simulation efficiency. In its verification deployment in the South China Sea, the mobile drilling rig has been operated many times at different depths, and some cores have been successfully obtained. It was also used during the 55th Voyage of China Oceanic Scientific Expedition, which was supported by the China Ocean Mineral Resources R&D Association. Several sites were explored, and a large number of cobalt-rich crust cores were obtained. Theory and sea trials are explained to support further research on the survey of abyssal resources.

Keywords: cobalt-rich crusts, mobile drilling rig, hydraulic propulsion system, dynamic simulation

Introduction

The ocean, which accounts for 71% of the earth's surface, is rich in mineral resources. Cobalt-rich crusts and nodules are potential sources of a wide variety of elements, such as Co, Ti, Mn, Ni, Pt, Zr, Nb, Te, Bi, Mo, W, Th, and rare-earth elements for crusts and Ni, Cu, Co, Mn, Mo, and Li for nodules (Hein & Koschinsky, 2014; Hein et al., 2013). Cobalt-rich crusts were first discovered in the late 1950s, and they were mainly distributed in the high terrain areas of the Western Pacific and South Pacific (Usui & Someya, 1997). The drilling rigs used for deep seabed shallow strata are complex systems that integrate mechanical, electrical, hydraulic, optical, and other components. They can obtain solid core samples at specific stations and have a safe operation process; thus, they are widely used in the exploration of ocean cobalt-rich crust resources and other fields (Freudenthal & Wefer, 2009). Paul Johnson contracted with Williamson and Associates in 1989 and 1990 to build the world's first 3-m robotic subsea drill, which was installed on board the old R/V Thomas G. Thompson (Tim & Gerold, 2007). The drill, built in the United Kingdom, can core up to 5 m deep and was administered by the British Geological Survey, but it lacks imaging capabilities and cannot go deeper than 2,000 m due to its cable. This means that many sites of interest to marine investigators cannot be drilled. Furthermore, the drill cannot image the seafloor, so operators cannot confirm whether it has landed on a suitable outcrop (Petersen et al., 2005).

Another example is the GBU-1.5/6000-2 drill, which was built by the Russian Northern Geological Exploration Engineering Consortium; it can core up to 1.5 m deep and is hung in the form of steel cables (Ren et al., 2019). In 2003, the Changsha Institute of Mining Research developed the first deep sea shallow drilling prototype in China, which was designed for depths of 4,000 m and can obtain cores measuring 0.7 m in length and 56 mm in diameter (Wan et al., 2010). Under the sponsorship of China's National High-tech R&D Program, a 20-m seafloor core sampling drill was developed by the Hunan University of Science and Technology at the end of 2010; it can drill up to a penetration depth of 20 m through wireline coring (Wan et al., 2015). Cobalt-rich crusts are mostly distributed on the slopes of seamounts, and the slope is fairly steep. However, the abovementioned equipment cannot select exploration sites independently, thus severely restricting the comprehensive study of cobalt-rich crusts and nodules. Therefore, a new method of using a mobile drilling rig to acquire core samples from the deep sea is proposed to improve survey efficiency.

This paper is organized as follows. First, the structure and working principle of the mobile drilling rig are briefly described. Then, the propulsion system, which lies at the core of the mobile drilling rig, is presented. A hydraulic propulsion system model is established for the mobile drilling rig using the software Simcenter Amesim. Closed-loop and proportion-integral-differential (PID) control methods are separately used to control the hydraulic propulsion system for simulation analysis. Finally, the simulation results based on the data analysis are elaborated.

The mobile drilling rig has been used successfully, and a large number of cobalt-rich crust cores were obtained during the 55th Voyage of China Oceanic Scientific Expedition, which was supported by the China Ocean Mineral Resources R&D Association.

Structure and Composition of Mobile Drilling Rig

Whole Frame

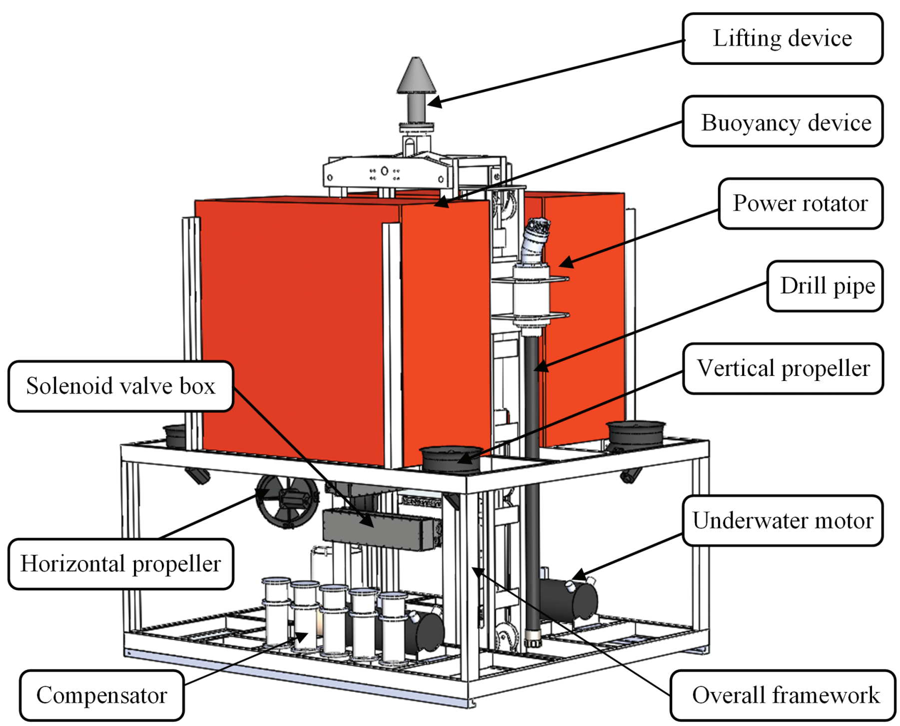
Mobile drilling rigs for deep seabed shallow strata are necessary for marine geologic and environmental investigation. Such rigs are designed for depths of 4,500 m and can obtain cores with 1.5-m length and 56-mm diameter. Such equipment mainly consists of a drilling unit, a hydraulic system unit, and a propulsion unit. As shown in Figure 1, the studied mobile drilling rig mainly includes the overall framework, lifting device, buoyancy device, power rotator, drill pipe, solenoid valve box, underwater motor, compensator, and propeller.

Drilling Unit

The drilling unit, which is used to acquire the core, is composed of a drilling frame, a drilling driving device, a double-length mechanism of a wire rope driven by a hydraulic cylinder, and a washing mechanism. The drilling frame is mounted on the center of the drilling rig; the lower part is fixed with the chassis by bolts, and the upper part is connected to a hanger for load bearing. The power rotator is installed in front of the drill frame, and the propulsion driving cylinder and pulley block are inside the drill frame. The power rotator consists of a sliding frame, a hydraulic motor, a bearing box, and a water inlet,

FIGURE 1

Structure of mobile drilling rig.



among others. Under the control of the hydraulic system, the hydraulic motor has functions of high speed and slow speed, which can cooperate with different drilling pressures for the best drilling effect. The stroke of the drilling driving device can reach 1.5 m through the double-length mechanism of the wire rope driven by the hydraulic cylinder, which has a maximum stroke of 0.9 m. Through the water pump driven by the hydraulic motor, seawater is discharged from the water inlet of the drilling driving device and then flows through the bottom of the drilling hole to realize the functions of drilling slag and drill bit cooling.

Hydraulic System

The hydraulic system mainly consists of the underwater motor and hydraulic pump, two general-function valve packs (8 and 16 stations), compensators, oil tank with pressure compensation, hydraulic pipeline, and various hydraulic actuators. The 8- and 16-station general-function valve packs are extremely compact and lightweight, making them suitable for work-class and inspection remotely operated vehicles (ROVs) and for specialized tooling applications. The 8-station general-function valve pack is mainly used to control the propulsion unit, while the 16-station general-function valve pack is mainly used to control the hydraulic actuators.

Each reversing valve and proportional control valve are electromagnetically driven and controlled by an underwater computer control system. When used underwater, the valve pack cover, electronic control interface box, and other actuators must be oil filled and compensated using suitable positive pressure compensators.

Propulsion Unit

The propulsion unit is mainly composed of four vertical propellers, two parallel propellers, and the hydraulic system that drives them to work. During deployment, the compass mounted on the system is used to monitor its attitude in real-time. If its attitude changes significantly, the propellers are used to correct the deviation to ensure its stability and reduce the incidence of ocean currents. When it is close to the seafloor, the mobile drilling rig can move smoothly, and the drilling sites can be selected intuitively and quickly with use of the underwater propulsion and visualization systems.

Control System

The overall structure of the control system is presented in Figure 2. The monitoring and controlling unit on the deck can display the operating status of the system in real-time, and it can operate the mobile drilling rig. The power distribution cabinet provides high-voltage power supply for the whole system and monitors its insulation status in real-time. The underwater voltage conversion unit converts the high voltages to low voltages and provides power to all low-voltage peripherals. The unit of the underwater high-pressure oil source can supply high-pressure oil to all the hydraulic actuators. The sensor signal acquisition unit monitors the working conditions of the system and transmits signals to the master computer software in real-time. The analog and digital signals are converted by the photoelectric signal conversion and transmission unit.

Hardware Design of Sensor Signal Acquisition Unit

The mobile drilling rig needs various sensors to collect signals indicating the temperature of the equipment control module, system pressure of the oil source and some main actuators, depth of the working ocean, and drilling speed. Moreover, the signals are transmitted to the master computer in real-time through the communication unit, which enables the monitoring

FIGURE 2

Overall structure of control system.

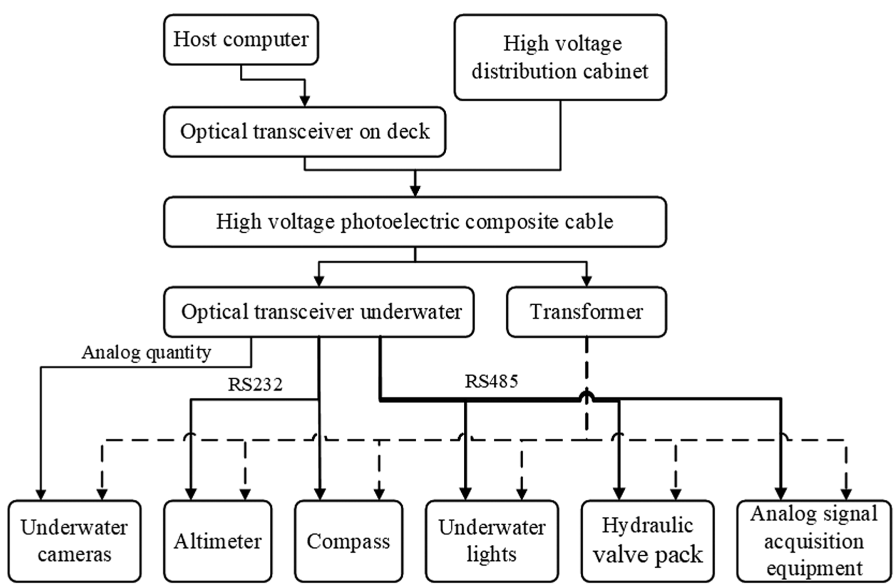
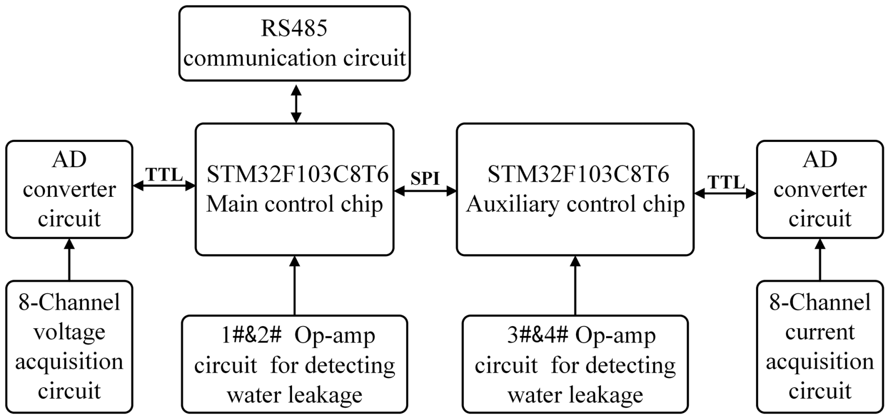


FIGURE 3

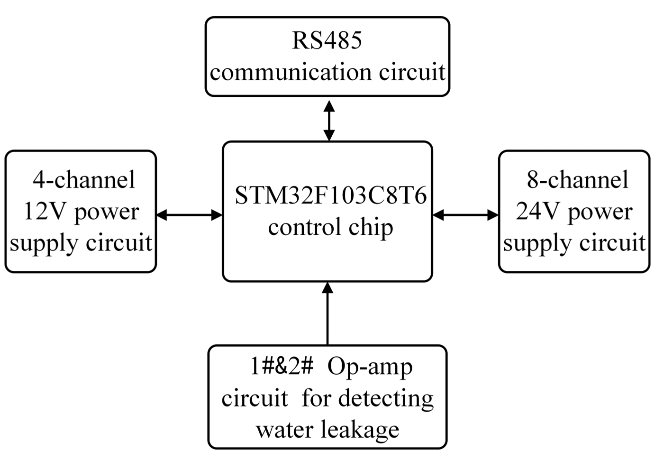
Structure of sensor signal acquisition circuit.



system to grasp the operating status of the whole system in real-time and guides the technical staff in implementing operations. As shown in Figure 3, the STM32F103C8T6 control chip is used for the microcontroller unit (MCU), which adopts the form of the RS485 (a standard that defines the electrical characteristics of drivers and receivers) bus network for communication. The analog output sensor has two forms of voltage output and current output. For reducing the space occupied by the circuit board in the underwater interface box, two STM32F103C8T6 chips, which are used to collect voltage and current signals, are integrated into the circuit board, and time to live (TTL) level signals are used to facilitate the information transfer between the main and auxiliary control chips. The voltage and current signals are transmitted to the acquisition and conversion circuit after passing through the operational amplifier conditioning circuit for enhanced accuracy of analog acquisition. This circuit adopts a 16-bit AD7689 analog-to-digital conversion chip and communicates information with the principal and auxiliary controllers through the serial peripheral interface (SPI) communication mode. A four-way leakage detection circuit, which contains an operational amplifier, is used to detect any leakage in the interface box and transmit status information in real-time.

FIGURE 4

Structure of peripheral power control unit.



Design of Peripheral Power Control Unit

The mobile drilling rig is fitted with various types of external equipment with 12- and 24-V power supply. Each equipment requires an independent power supply to ensure that it can be isolated without affecting the normal use of the other equipment when an external device fails. As shown in Figure 4, the MCU, which is based on STM32F103C8T6, is adopted to network with the communication bus through the RS485. The four-channel 12-V and eight-channel 24-V power supply circuits with overload protection function can supply power to equipment with a rated power below 30 and 100 W. Two leakage detection circuits perform real-time leakage detection for the light compartment.

Design of System Software

Design of Sensor Signal Acquisition Unit Software

The software of the sensor signal acquisition unit mainly includes the following functions. First, the initialization of the main controller and auxiliary controller chips is controlled by this software. Thereafter, the auxiliary control chip collects analog data and sends them to the main control chip at a certain time interval through the serial port. The auxiliary control chip can also assess the "flag of watchdog" (a timer that can periodically check the internal condition of the chip and send a restart signal to the chip if an error occurs). If the flag of watchdog is obtained within the reload time, the watchdog will be updated; otherwise, the auxiliary control chip system will be reset. Finally, the serial port of the main controller chip interrupts the received data and checks the data frame. The data sent by the auxiliary control chip are stored in the buffer. The inquiry instruction is sent by the upper computer, and the collected data transmitted by the auxiliary control chip or the inquiry command sent by the upper computer are stored if the instruction is correct. Then, the latest data status is written into the data frame and sent to the host computer through the serial port.

Design of Peripheral Power Control Unit Software

The functions of this software are as follows. First, the system is predefined and initialized based on the software, and it can receive and assess the correctness of data. If the received data are correct, the system will determine whether the data frame ID is the ID of the peripheral power control board. Then, the instruction byte of the data frame is evaluated, and the corresponding input and output (IO) port is operated according to the status of the command byte. If the received data frame is the inquiry instruction, the leakage detection data collected by the system will be directed to the upper computer. In addition, the system will automatically reload if it does not receive the operation instruction from the upper computer again when the independent watchdog reloads the value.

Operating Software

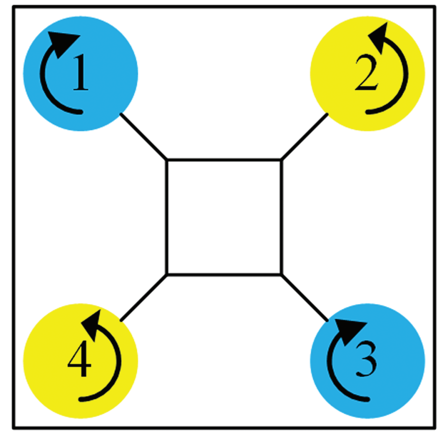
The deck operation control system mainly consists of an operation control computer, high-speed data communication module, and dedicated monitoring image display, among others. The operation control computer receives the data of each sensor and the monitoring video signal sent from the underwater control computer. The operator determines the working status of the drilling rig on the basis of the displayed sensor data and monitoring images. Then, it controls the rig system according to the prescribed procedures. All image information and rig operation data are recorded. In seeking the station, the hydraulic propulsion system performs automatic height setting and displacement by working in conjunction with an altimeter. During the drilling process, different drilling pressures and speeds are selected according to the stratigraphic conditions.

Design and Dynamic Simulation Analysis of Hydraulic Propulsion System

The hydraulic system of the mobile drilling rig mainly comprises a rotary drilling hydraulic system and a propulsion hydraulic system. The rotary drilling hydraulic system is relatively simple; it only needs to set the system pressure and flow rate according to the different stratigraphic conditions. Therefore, the propulsion system should be analyzed and studied. Due to the reasonable spatial arrangement of the propeller, the mobile drilling rig can move freely near the seabed. Regardless of the movement of the drilling rig, the propeller outputs a corresponding thrust or torque, and the combined force of all thrusters is greater than the resistance of the rig's navigation in the sea.

FIGURE 5

Rotating direction of propellers.

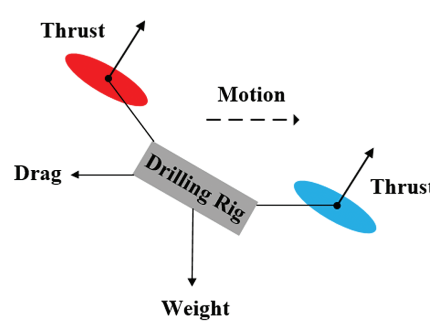


Working Principle of Propulsion System

Six thrusters are distributed on the mobile drilling rig to realize independent movement with three degrees of freedom. Two of these thrusters are horizontal thrusters, and they mainly control the moving direction; four thrusters are vertical propellers, and they mainly control the vertical lifting and horizontal movement of the mobile drill rig. In accordance with Newton's third law, as the propeller spins, it also applies a reaction force to the mobile drilling rig that causes it to rotate in the opposite direction. Two adjacent propellers rotate in opposite directions, as shown in Figure 5, to avoid the rotation of the rig. The

FIGURE 6

Mechanical model of system.



mechanical model of the system is presented in Figure 6. If the rotation speed of the No. 1 and No. 2 propellers is reduced or the rotation speed of the No. 3 and No. 4 propellers is increased, the drilling rig will generate a forward force to make itself move forward. On the contrary, if the rotation speed of the No. 1 and No. 2 propellers is increased or the rotation speed of the No. 3 and No. 4 propellers is reduced, the drilling rig will generate a backward force, causing itself to move backward. In addition, the drilling rig can dive or rise when the four vertical propellers rotate at the same speed.

Design of Hydraulic Propulsion System

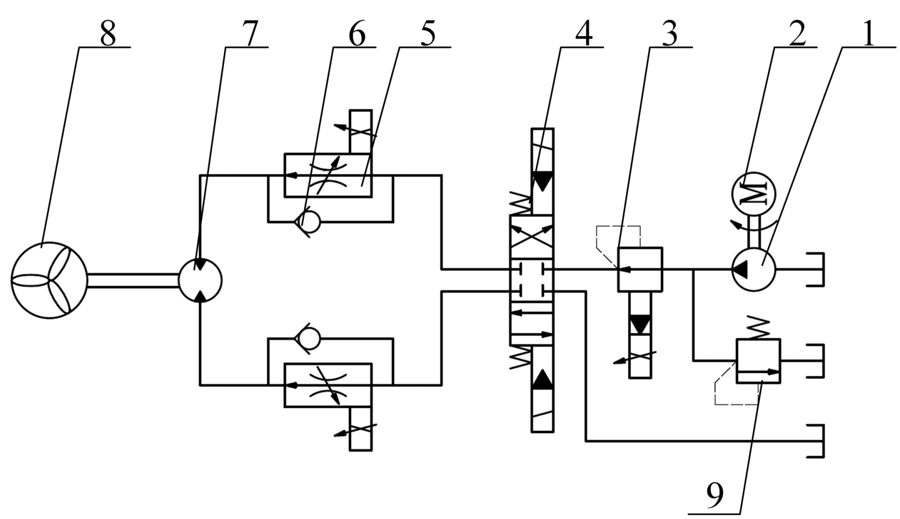
Pump-controlled hydraulic systems and valve-controlled hydraulic systems are common hydraulic drive systems. A pump-controlled hydraulic system can operate the actions of actuators by increasing or decreasing the flow rate of the hydraulic pump. Although it has high efficiency, its control performance is poor and cannot satisfy control requirements well. Valve-controlled hydraulic systems are generally used in open systems, which can control the actions of actuators by the flow of a proportional valve or servo valve. It has a few advantages, including energy conservation, low heat generation, and precise control. However, this method enhances the complexity of hydraulic systems, thereby increasing costs (Ferrari et al., 2013).

The pressure and flow of hydraulic propulsion systems vary greatly. Thus, for the hydraulic propulsion system in this paper, a mixed control hydraulic system of a pump and a valve is adopted; this approach combines the advantages of the two methods, thereby possibly ensuring good dynamic response performance from the hydraulic propulsion system. Furthermore, a flow-adaptive hydraulic pump is used to guarantee that the output flow of the system always matches the flow required by the hydraulic components; this reduces the excess flow and the overflow loss of the hydraulic system, thereby improving system effectiveness (Ha et al., 2020).

A constant-pressure variable pump is applied to the hydraulic system; it can continuously provide hydraulic oil with constant pressure for the hydraulic propulsion system, and it adjusts the output flow of the system according to the flow required by the workload. Since the mobile drilling rig transmits instructions and data through the cable and the console in both directions, electro-hydraulic proportional technology is adopted in the hydraulic propulsion system to accurately control the propeller speed. An electro-hydraulic proportional pressure-reducing valve is used to limit the hydraulic pressure of the propeller, while an electro-hydraulic proportional flow-rate-regulating valve adjusts the oil flow of the branch to satisfy the requirements of the propeller (Pang et al., 2009; Ridao et al., 2004; Sayer, 2008). The hydraulic schematic of a single propeller is presented in Figure 7. For the propeller to output accurate speed, the real-time speed measured by the speed sensor is uploaded to the console through the cable and then compared with the target speed. Afterward, the deviation processed by the control system is fed back to the proportional valve for real-time adjustment.

FIGURE 7

Hydraulic schematic of single propeller: (1) hydraulic pump, (2) underwater motor, (3) electro-hydraulic proportional pressure-reducing valve, (4) electromagnetic directional valve, (5) electro-hydraulic proportional flow-rate-regulating valve, (6) check valve, (7) hydraulic motor, (8) propeller, and (9) relief valve.



Dynamic Simulation Analysis of Hydraulic Propulsion System Based on Simcenter Amesim

Modeling and Analysis of Hydraulic Unit

As seen in Figure 7, the hydraulic propulsion system of the mobile drilling rig is mainly composed of the hydraulic station, an electro-hydraulic proportional flow-rate-regulating valve, an electro-hydraulic proportional pressure-reducing valve, a propeller, and other hydraulic accessories. There are no standard component models of proportional flow-rate-regulating valves and proportional pressure-reducing valves, and the Simcenter Amesim hydraulic library does not have any standard element model of propellers. Hence, the required hydraulic unit should be built using the library of hydraulic components according to the physical structure and working principle of the rig. Next, it is verified by simulation to observe whether the performance of the built component model is consistent with the performance of the actual object.

In accordance with the actual working principle (Maiti et al., 2002), the simulation model of the electro-hydraulic proportional pressure valve is shown in Figure 8. This proportional pressure valve is a three-position four-way directional control valve, and its parameters are as follows: proportional valve diameter of 10 mm, maximum working hydraulic pressure of oil inlet (P) of 315 bar, maximum allowable flow rate of oil circuit of 120 L/min, and power voltage of 24 V. The parameters of the model component are set with reference to the actual structure of a proportional pressure valve. From the data analysis conducted with Simcenter Amesim, the relationships between the output pressure and input voltage are obtained during the working process, as shown in Figure 9. The simulation analysis results show that the output pressure increases with the input voltage.

The proportional flow-rate-regulating valve is a combination of a proportional throttle valve and a differential pressure-reducing valve through a serial connection, which can change the area of the orifice to control the flow rate through electrical signals (Amirante et al., 2008). The flow rate of the throttle is related to the pressure difference between the inlet and outlet of the throttle valve; this will inevitably lead to changes in pressure and flow rate when the load changes. As a result, the regulation of the oil flow rate by the proportional throttle valve will not be precise (Franklin et al., 2009). The differential pressure-reducing valve is used to keep the pressure difference between the inlet and outlet of the throttle valve unchanged, thus achieving precise control of the flow rate via electrical signals and compensating for the above flow deviation (Krus et al.,

FIGURE 8

Simulation model of electro-hydraulic proportional pressure valve.

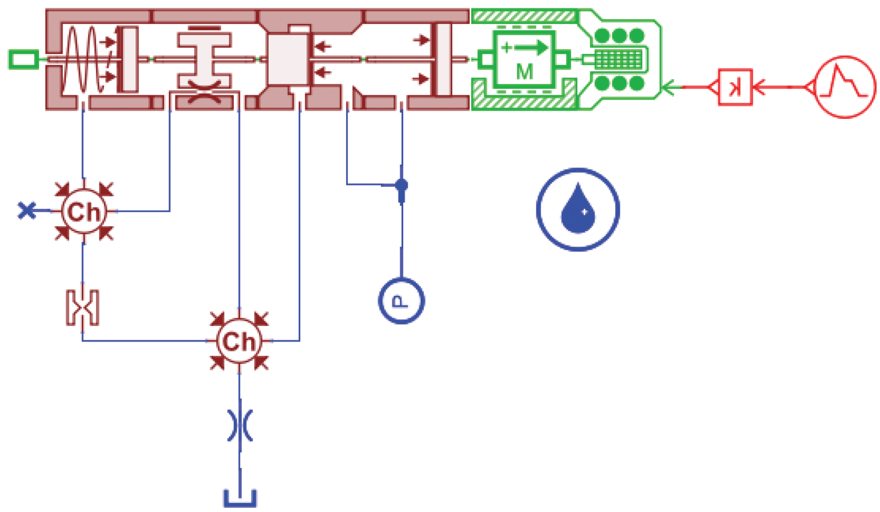
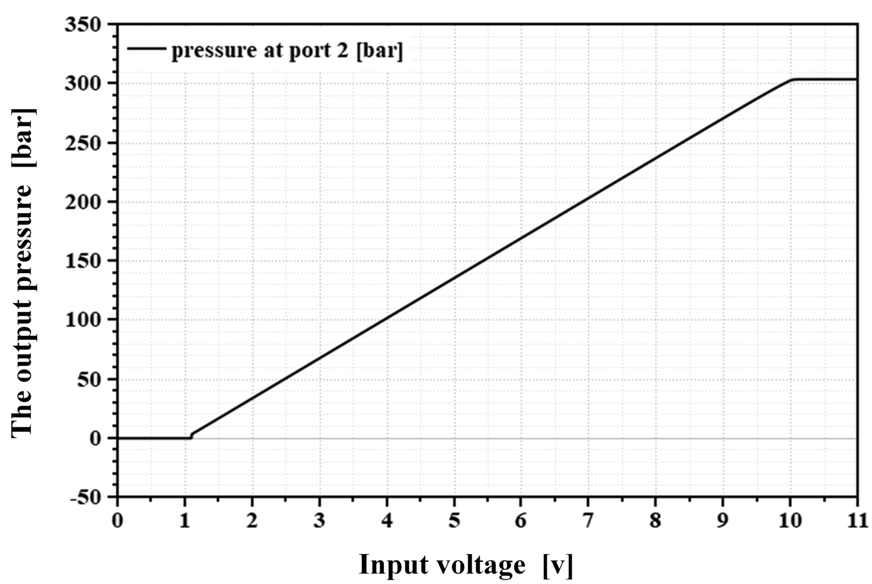


FIGURE 9

Relationship curve of output pressure and input voltage.



1994). The simulation model of the electro-hydraulic proportional flow-rate-regulating valve is presented in Figure 10. Its specific parameters are as follows: proportional valve diameter of 10 mm and maximum allowable flow rate of oil circuit of 45 L/min. On the basis of the data analysis conducted through Simcenter Amesim, the relationship between the output flow rate and input voltage is obtained during the working process, as shown in Figure 11. The simulation analysis results show that the output pressure increases with the input voltage. The flow rate is 0 L/min when the voltage is less than 3 V, and the maximum output flow rate is 45 L/min when the voltage is 10 V; these are consistent with the steady-state flow rate curve.

Dynamic Simulation of Hydraulic System

The simulating system is modeled without regard for the hydraulic components of the propulsion system, such as the pressure gage, filter, and relief valve for overload protection, which have little influence on the simulation results. Moreover, the model components of the system hydraulic station can be replaced by hydraulic components with the same functionality from the hydraulic library. Since the hydraulic control circuit and control method are common between the propellers, the entire hydraulic propulsion system can be analyzed by the simulation analysis of a single propeller. The simulation of the hydraulic propulsion system is presented on the basis of a theoretical model of both closed-loop control and PID control.

First, the hydraulic propulsion system of a single propeller is numerically simulated with closed-loop control. The working principle of closed-loop

FIGURE 10

Simulation model of electro-hydraulic proportional flow-rate-regulating valve.

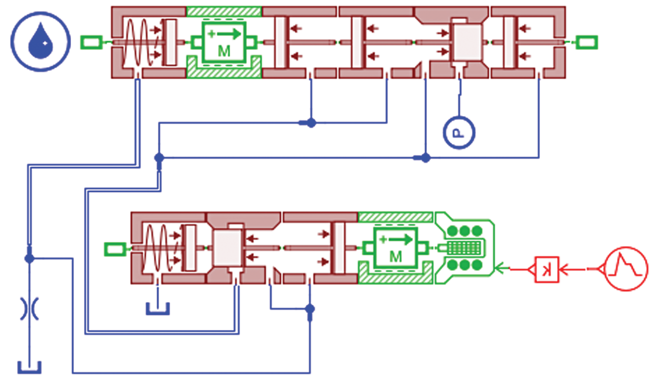


FIGURE 11

Relationship curve of output flow rate and input voltage.

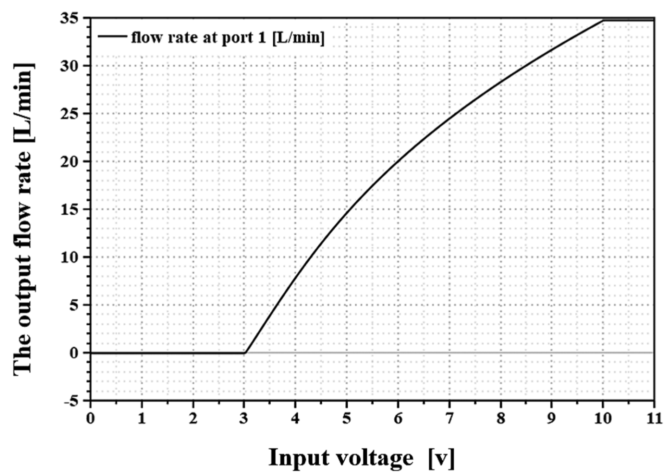
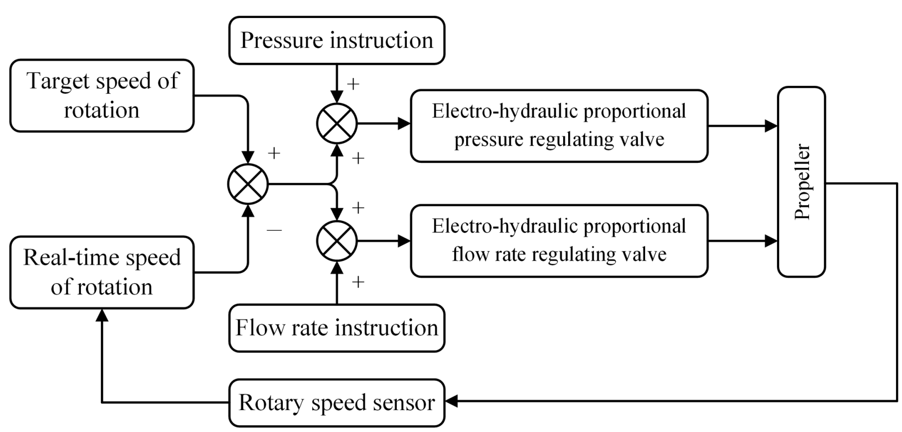


FIGURE 12

Working principle of closed-loop control.



control is illustrated in Figure 12. When the proportional pressure valve and flow-rate-regulating valve receive the control command number, the pressure and flow rate of the oil flowing into the propeller are regulated to reach the target speed of rotation. During the regulating process, the real-time rotational speed detected by the rotary speed sensor is compared with the target rotational speed. Afterward, the deviation is applied to the proportional pressure valve and flow-rate-regulating valve to adjust the oil pressure and flow rate again. The cycle process is infinite, and the rotational speed is infinitely close to the target rotational speed. The advantage of closed-loop control is that it fully develops the important role of feedback and eliminates unpredictable or uncertain factors, thereby potentially making the corrective action more accurate and powerful. On the basis of the above working principle of the hydraulic propulsion system, the simulation model is established with closed-loop control, as shown in Figure 13.

Since the output rotational speed of the propeller is simulated when the mobile drilling rig is moving, the target rotational speed is set as 1,000 r/min. Considering the impact of the marine environment on the propeller, a random interference signal is added to the signal transmission line of the speed sensor. The positive and negative amplitudes are 10% of the target rotational speed, and the maximum and minimum values are positive and negative, respectively. The other parameters remain unchanged. From the data analysis conducted through Simcenter Amesim, the relationship between the real-time rotational speed and time is obtained during the working process, as shown in Figure 14. The simulation analysis result shows that the output rotational speed of the propeller is close to the target rotational speed. However, the rotational speed fluctuates from the beginning to the end of the simulation, and there is a large over-adjustment. Therefore, it is difficult to justify the performance of the hydraulic propulsion system with closed-loop control in terms of design.

PID control is adopted to simulate the sampling process and address the above problem (with closed-loop

FIGURE 13

Simulation model with closed-loop control.

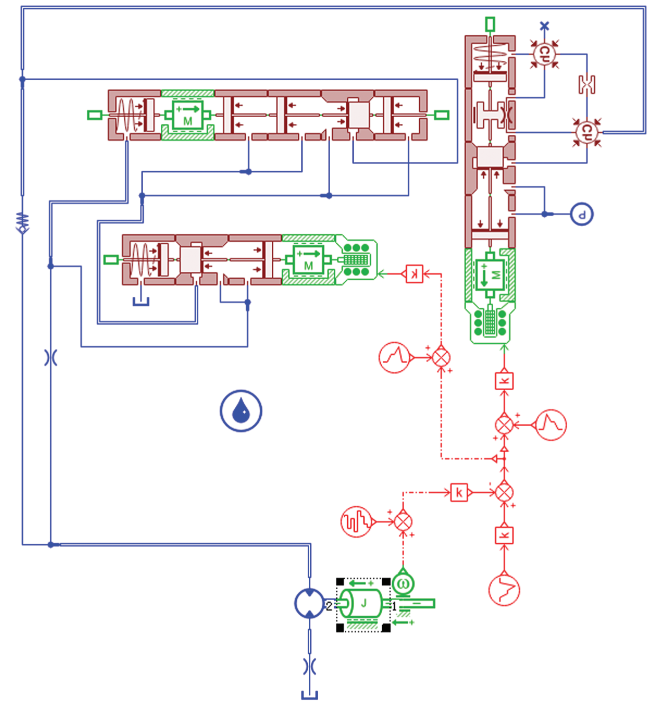


FIGURE 14

Relationship curve of real-time rotational speed and time with closed-loop control.

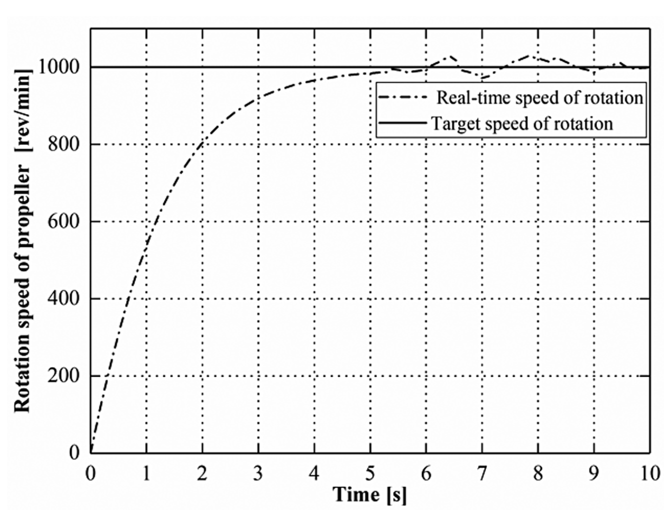
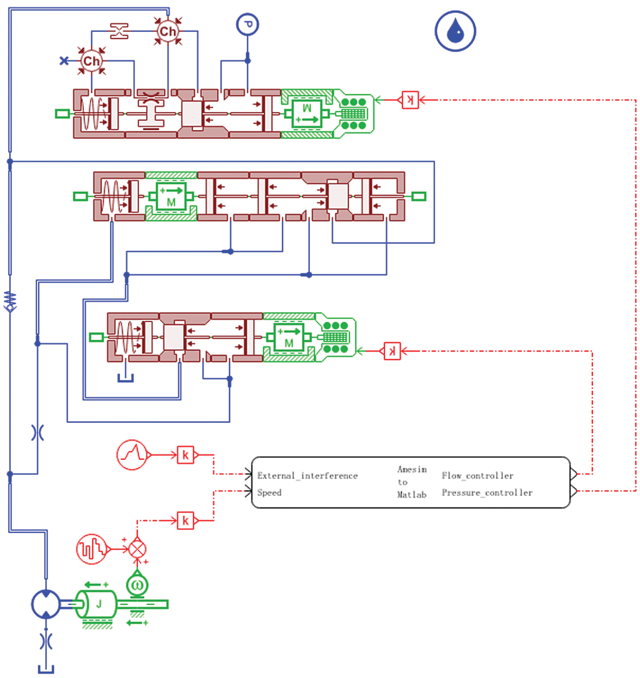


FIGURE 15

Simulation mode with PID control.



control). Simcenter Amesim can use various model libraries to design the required system, thus achieving the purpose of the simulation (Marquis-Favre et al., 2006). MATLAB/Simulink is commonly used in many fields due to its powerful numerical processing capability (Kiyan et al., 2013). Based on joint simulation technology, Simcenter Amesim's excellent simulation functions of fluid mechanics can be fully utilized, and the powerful numerical processing function of MATLAB/Simulink can be used to achieve the best simulation results (Wang et al., 2017; Zhao & Wang, 2012). A PID controller controls the proportional (P), integral (I), and differential (D) deviation to meet control requirements (Ang et al., 2005; Yang et al., 2009).

A PID controller is a negative feedback regulation mechanism composed of operational amplifiers, capacitors, and resistors, which are widely used in industrial control systems. As a classic traditional controller, it has a simple structure, relatively strong robust control, and easy implementation in actual operation. The elementary theory of PID control is as follows: the deviation between real-time data and the target value is transformed into proportional, integral, and differential deviations and then superimposed on an input control object to control its output; this is an infinite loop control process (Wang & Xu, 2009). The mathematical equation for PID control can be expressed as

$$u(t) = K_p\left[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + \frac{T_d de(t)}{dt}\right],$$

where $u(t)$ is the control quantity of the controlled object, K_p is a proportional factor, T_i is an integral time constant, T_d is a differential time constant, and $e(t)$ is the control deviation.

The deviation between the real-time and target rotational speeds should be processed by the PID controller and then fed back to the proportional pressure valve and proportional flow-rate-regulating valve. Consequently, the real-time rotational speed can be closer to the target rotational speed. According to the above working principle, the simulation model is established with PID control, as shown in Figure 15. The model of the control system is shown in Figure 16.

From the data analysis performed through both Simcenter Amesim and MATLAB/Simulink, the relationship between the real-time rotational speed and time is obtained during the working process, as shown in Figure 17. The simulation analysis result shows that the output rotational speed of the propeller is close to the target

FIGURE 16

Model of control system.

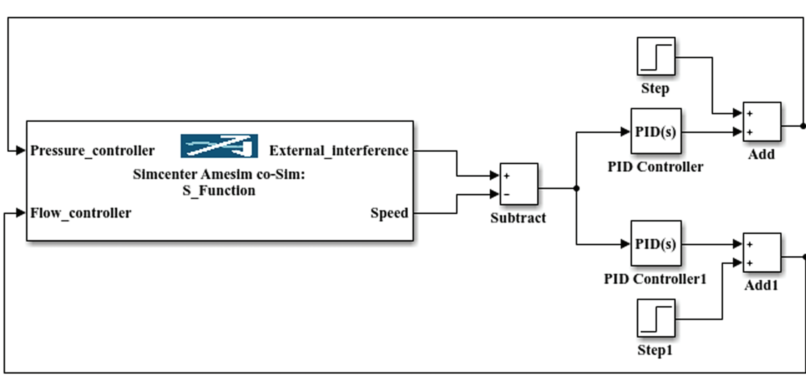
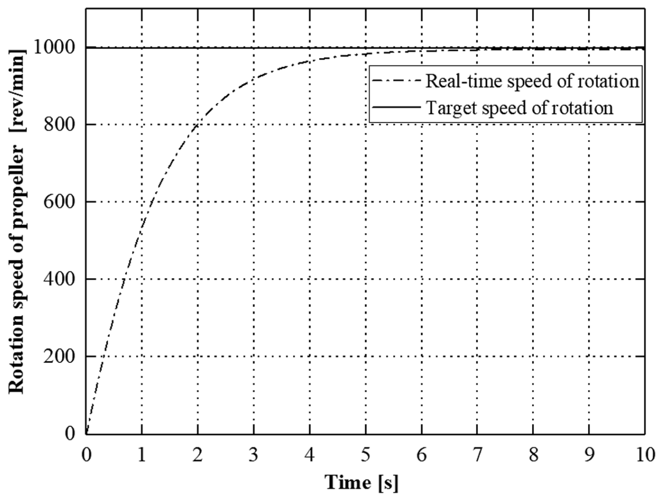


FIGURE 17

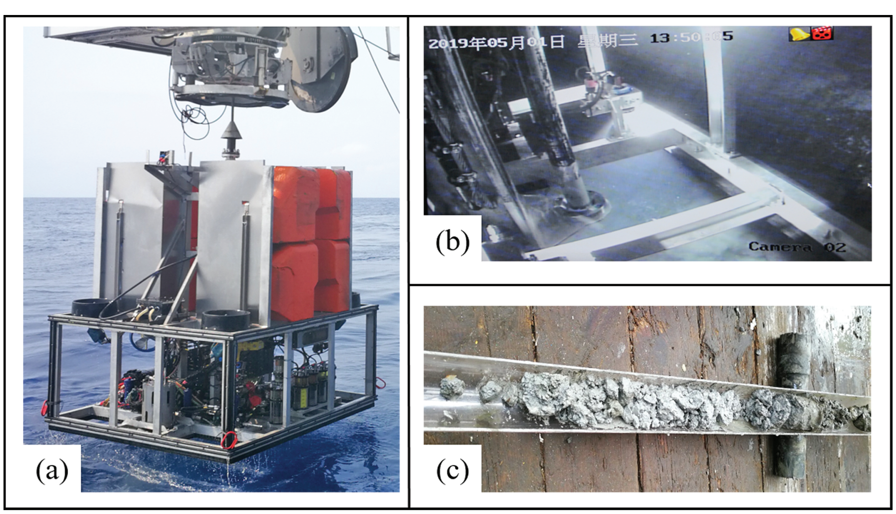
Relationship curve of real-time rotational speed and time with PID control.



rotational speed. Comparison between PID and closed-loop control shows that the adjustment time of rotational speed is reduced under PID control. In terms of accuracy, the rotational speed adjusted by PID control can quickly tend to the target speed, and the error is small. The proportional regulation law is mainly controlled by the magnitude of deviation. When a deviation occurs, the regulator immediately produces a regulation that is proportional to the difference between the input and output quantities. The integral regulation is used to eliminate the static difference of the system, and the output changes in proportion to the integration of the input deviation over time. The differential regulation reflects the trend of the deviation change rate and introduces a correction signal in advance in the system, and its output changes in proportion to the rate of input deviation change. The simulation analysis results indicate that a hydraulic propulsion system with PID control can meet the propulsion requirements of the mobile drilling rig. Thus, PID is a suitable control method for the motion simulation of additional degrees of freedom for mobile drilling rigs.

FIGURE 18

Photographs of sea trial in May 2019: (a) mobile drilling rig before descent into ocean with lifting device, (b) search of drilling rig for suitable exploration site, and (c) 1.0-m–long core of carbonate crust.

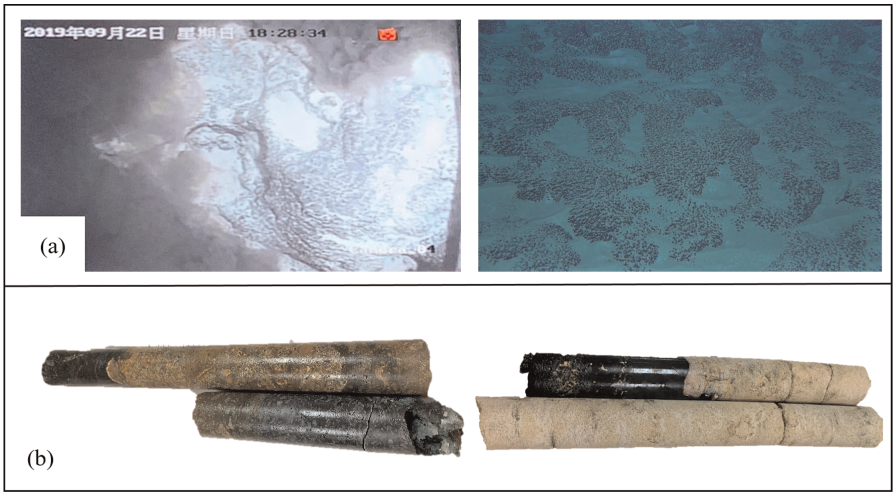


Deep Sea Coring Test of Mobile Drilling Rig

On the basis of the above theoretical and simulation analysis results, the mobile drilling rig is designed with a maximum weight of 2,000 kg and a maximum core length of 1.5 m. It is equipped with visualization and propulsion systems that can move near the seabed to choose exploration sites independently. From April 10, 2019, to May 9, 2019, numerous experimental investigations were conducted during the deep sea exploration voyage of the R/V Haiyang 6, which was organized by the Guangzhou Marine Geological Survey in China (Figure 18). Figure 19 shows the drilling rig operating during a sea trial. Due to the success of these sea trials, the mobile drilling rig was used during the 55th Voyage of China Oceanic Scientific Expedition, which was supported by the China Ocean Mineral Resources R&D Association, from September 6, 2019, to October 23, 2019. A large number of cobalt-rich crust cores were obtained in the area covered by the cobalt-rich crust exploration contract between China and the International Seabed Authority. A total of 76 sites were sampled within 24 days through the mobile drilling rig and two kinds of drilling rig for seabed shallow strata, including 70 sites with 1.5-m depths

FIGURE 19

Photographs of sea trial in September 2019: (a) underwater photograph of plate curst and (b) cores of plate crust and substrate rock.



and six sites with 6-m depths. On the basis of the cores of cobalt-rich crusts, scientists can estimate the amount of cobalt-rich crust resources, which will provide basic data for future marine geological science research and resource estimation. Figure 19 shows an underwater photograph of the plate crust and cores of the plate crust.

Conclusion

In this paper, a mobile drilling rig is proposed to acquire the seafloor core (up to 1.5 m long). Built using Simcenter Amesim and MATLAB/Simulink, the hydraulic propulsion system model of the mobile drilling rig is established and simulated. Closed-loop and PID control methods are separately used to control the hydraulic propulsion system for simulation analysis. Comparison of the simulation results indicated that PID control is more convincing in verifying the design rationality of the hydraulic propulsion system. Hence, it is a suitable control method for the motion simulation of additional degrees of freedom for mobile drilling rigs. On the basis of the theoretical and simulation analysis results, the mobile drilling rig was designed and tested in 2019. In its verification deployment in the South China Sea, the mobile drilling rig was operated at various times and depths, and some cores were successfully obtained, which verified the feasibility of this equipment. Furthermore, the mobile drilling rig was used during the 55th Voyage of China Oceanic Scientific Expedition, which was supported by the China Ocean Mineral Resources R&D Association. Numerous sites were explored, and a large number of cobalt-rich crust cores were obtained, which provided powerful support for further research on the survey of abyssal resources.

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Corresponding Author:

Feng Zhou
State Key Laboratory of Fluid Power Transmission and Control
Zhejiang University
866 Yuhangtang Road
Xihu District, Hangzhou, China
Email: madzf@zju.edu.cn

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