Journal of Marine Science and Application (2020) 19:453–464
https://doi.org/10.1007/s11804-020-00158-y

RESEARCH ARTICLE

Design and Experimental Investigation for Subsea Control Module Test System

Peng Jia[1] · Zhehua Zhang[1] · Xiangyu Wang[1] · Feihong Yun[1] · Honghai Wang[1] · Gang Wang[1]

Received: 10 November 2019 / Accepted: 7 March 2020 / Published online: 12 October 2020

Abstract
As a core part of subsea production systems, subsea control modules (SCMs) are costly, difficult, and expensive to install and inconvenient to use in underwater maintenance. Therefore, performance and function tests must be carried out before launching SCMs. This study developed a testing device and an SCM test by investigating SCMs and their underwater. The testing device includes four parts: a hydraulic station, an SCM test stand, a signal generating device, and an electronic test unit. First, the basic indices of the testing device were determined from the performance and working parameters of the SCM. Second, the design scheme of the testing device for the SCM was tentatively proposed, and each testing device was designed. Finally, a practical measurement of the SCM, in combination with the hydraulic station, SCM test stand, signal generator, electronic unit, and high-pressure water tank, was carried out according to the test requirements. The measurement mainly involved equipment inspection before testing and an experimental test for the SCM. The validity and feasibility of the testing device and method were simultaneously verified through an association test.

Keywords Subsea control module · Testing device · Hydraulic system · Electronic control system · Experimental research

1 Introduction

At present, offshore oil and gas, especially deep-sea oil and gas, are rich in resources, and exploration and development are proceeding rapidly. It can be said that the future of the petroleum industry lies in offshore oil. As a key facility for developing deepwater oil and gas resources, underwater production systems have stricter performance requirements. The core equipment of the underwater production system is the subsea control module. Whether SCM can safely and effectively monitor is related to whether the underwater production system can implement production operations in a safe and orderly manner. Once the SCM breaks down, it is extremely inconvenient and costly to repair. Therefore, the function and performance of the underwater control module must be tested before installation. How to formulate reasonable test requirements and test methods to ensure its functional effectiveness and safety and reliability in production and operation is one of the key technologies for deep-sea oil and gas field development.

Although the structure and appearance of SCM are quite different, the working principle is basically the same, and most of the functions are basically the same. Therefore, the test devices designed and manufactured by various manufacturers supporting the corresponding SCM are generally similar. In this regard, foreign countries started early, and related technologies are very mature. SCM has been gradually put into production. In foreign countries, companies that research and produce SCM test devices mainly include Weatherford, Rimor, and HitcProduct. The test devices produced by Rimor and Weatherford are basically used to test the self-developed SCM of the company. Based on the original application, a valve actuator simulator is added to visually observe

Article Highlights
- In order to ensure that the SCMs can work safely, a set of test schemes have been proposed, and a set of test equipment has been developed.
- The high- and low-pressure oil output of the hydraulic station was stable and reliable; the SGD could issue different analog signals according to the requirements; the ETU could issue an operation command to the SCM and receive a monitoring signal returned by the SCM.
- The joint SCM test was completed to verify the feasibility of the test methods and the effectiveness of the testing device.

✉ Peng Jia
13633605161@139.com

[1] College of Mechanical and Electronic Engineering, Harbin Engineering University, Harbin 150001, China

the action of the actuator, and the test is accurate and reliable. The SCM test device developed by HitcProduct is mainly aimed at the MK1, MK2, and MK5 series of underwater control modules produced by FMC. According to the characteristics of the SCM control oil circuit and control mode, the corresponding test device has been developed.

Liang et al. (2012) introduced separately the test purpose, main test content, test methods, and requirements of the underwater production system test links such as system unit test (SUT), factory acceptance test (FAT), system integration test (SIT), site receiving test (SRT), and commissioning. Chen et al. (2014) introduced the main test content and shallow water test process steps of the underwater production control system, providing a reference for the shallow water test of the domestic independent research and development of underwater equipment. Su et al. (2015) research the relevant test pools of foreign underwater production systems and analyze their test facilities, test functions, and test methods. Relying on Panyu 34-1 gas field, Chen et al. (2018) summarize the zero-level shut-off test method of underwater production system.

However, these papers are all system-level researches on subsea control system, and there is no more detailed research on subsea control module test systems. Therefore, the research on subsea control module test system facilities in this article is for subsea production. The testing and verification of the system is of great significance for breaking through the technical bottleneck of foreign countries and gradually moving from shallow sea to deep-sea oil and gas development.

2 General Layout of Subsea Control Module Test System

A subsea production system mainly consists of the surface part, underwater part, and umbilical cable connecting the two parts. The surface portion mainly comprises the hydraulic power unit (HPU), electronic power unit, main control station, monitoring system, and other facilities (Abicht and Braehler 2010). The underwater part mainly comprises the subsea distribution units, Christmas trees, manifolds, subsea separators, and other production facilities. The subsea control module (SCM) is typically installed onto the frame of the production facilities to control the valve actuators and monitor the pressure, temperature, flow, and other parameters. The SCM feeds the information of the submarine equipment back to the equipment in the sea. It also coordinates between the surface production platform and the underwater production system.

As the core part of underwater production systems, SCMs have a long service life but are costly, difficult, and expensive to install and inconvenient to use in underwater maintenance. Therefore, SCMs need to be subjected to performance and functional tests before being launched to ensure their normal operation and postlaunch and to avoid secondary installation and maintenance. Hence, this study developed a set of testing devices by investigating the working environment and working process of SCMs.

2.1 Components of Subsea Control Module

The SCM test system comprises four parts: an HPU, an SCM test stand, (SCMTS), a signal generator, and an electronic test unit (ETU). The working principle is illustrated in Figure 1.

2.1.1 Hydraulic Power Unit

The HPU operates as follows. The hydraulic station provides pressurized oil to the SCM through the test stand. The high-pressure supply oil circuit and low-pressure supply oil circuit have two channels each. The pressurized oil output can be adjusted according to the test requirements with an accuracy of up to 20 μm.

2.1.2 SCM Test Stand

The SCMTS is equivalent to a Christmas tree platform without a subsea sensor (the subsea sensor system is generated by the signal generating device (SGD). A docking station dedicated to the SCM is installed onto the SCMTS. The pressurized oil output from the HPU goes to the SCMTS and then reaches the SCM through the SCMTS (Altamiranda et al. 2009). The operating state

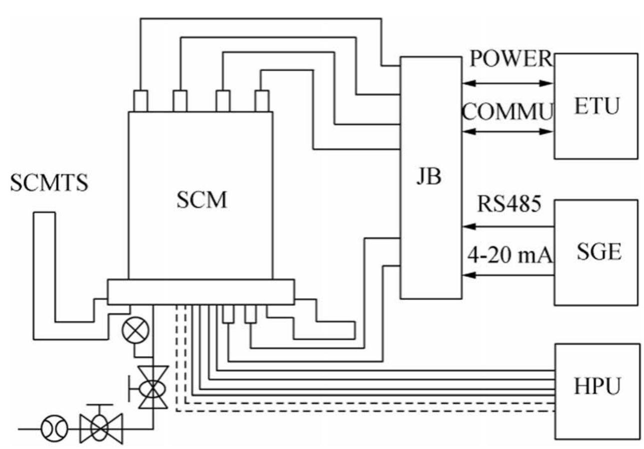

Figure 1 Schematic of SCM test system

of the SCM can be determined by observing the pressure gauges of each oil line in the SCMTS.

2.1.3 Signal Generating Device

In the actual subsea production environment, various sensors, such as Christmas trees for monitoring the subsea production environment, are installed onto the equipment. The monitored signal is transmitted to the SCM and then to the master station through the SCM (Bai and Bai 2010). The ground staff performs the corresponding operations on the basis of the received monitoring data. The SGD is used to simulate the various sensors and thereby monitor the state of the subsea production environment and transmit the monitored signals to the SCM.

2.1.4 Electronic Test Unit

The ETU is used to simulate the main control station. When the hydraulic station provides standard pressurized oil to the SCM through the test stand, it issues control commands to the SCM to control the opening or closing of the SCM valve. During the test, the hydraulic station receives the monitoring signal uploaded by the SCM, including the analog signal sent by the SGD (external detection signal) and the signal from the internal sensors of the SCM (internal detection signal). The ETU displays the received monitoring signals on the operating interface for the operator to control the subsea pipeline pressure, flow, and valve status at all times.

2.2 Test Requirements for Components of Subsea Control Module

The SCM can provide multichannel hydraulic control, including four-way high voltage and 614 low voltages. Two communication modes are available between the SCM and the main control station: power carrier communication and optical fiber communication (Da Cunha et al. 2018). The communication interface with the subsea equipment includes various communication interfaces, such as Industrial Ethernet, Modbus, and RS485.

Based on the working principle structural function, and test content requirements of the SCM, the design requirements of the testing device are detailed herein.

2.2.1 Hydraulic Power Unit

Among all testing devices, only the hydraulic station features hydraulic and electrical integration. Moreover, it needs to provide stable and adjustable high-precision pressurized oil, and it exhibits alarm and remote control functions (Da Cunha et al. 2017). According to the actual oil supply of the SCM, the design requirements for the hydraulic station are as follows:

- High-pressure output that is adjustable within152 MPa
- Low-pressure output that is adjustable within 132 MPa
- High- and low-pressure oil circuit overheat alarm, clogging alarm, and low-level tank alarm functions
- Oil filtration function
- Remote monitoring function
- Redundant power unit, oil supply unit, and filter unit

2.2.2 SCM Test Stand

The SCM's high-pressure oil supply and low-pressure fuel supply pipelines are generally designed with redundancy; that is, the high-pressure and low-pressure fuel supply pipelines each have two redundant hydraulic joints. The high-pressure function oil circuit and low-pressure function oil circuit are used to introduce pressurized oil to the subsea valve actuator and thereby control the opening and closing of the subsea valve (Eriksson 2011). According to the abovementioned SCM characteristics, the performance of the test stand should be as follows:

- The test stand should have at least two high-voltage outputs, two low-voltage outputs, two high-voltage inputs, and fourteen low-voltage inputs.
- A hydraulic gauge is installed onto each pipeline to monitor whether the SCM internal valve is open or closed.
- The test stand should contain several oil drain valves and flow meters to test the SCM's internal accumulator design compliance and measure the amount of internal SCM leakage.
- The docking station design should be replaceable to increase the convenience of testing different SCMs.

2.2.3 SGDs

The objective of the SCM is to monitor the subsea production environment by receiving data such as pressure, flow, temperature, and switching conditions. These data are transmitted from the subsea sensors to the SCM by current or voltage (Gong et al. 2014). According to the type and quantity of the actual signal, the SGD simulates the transmission of the same types of current and voltage signals to the SCM. Therefore, the design requirements for the SGD are as follows:

- The SGD should feature signal simulation for Christmas trees, production manifolds, bridge manifolds, subsea separators, and so on.

- It should be capable of simulating signals such as pressure, flow, emergency shutdown, and input to the SCM.
- It should have a transmitter and an interface for electrical signals (420 mA, Modbus, and Profibus) containing information such as pressure, flow, and temperature.
- It should have 40 independent digital signal outputs, 32 analog signal outputs, and six signal output channels.
- It should have system functions such as user management, historical data, and self-diagnosis.

2.2.4 ETU

The SCM needs to upload the received external sensor signal and internal sensor signal to the master control station (MCS) for the operator's reference (Gardner and Carter 2005). The MCS can control the opening and closing of the SCM valve. The ETU is equivalent to the actual production master station in the test. Therefore, the design requirements for the ETU are as follows:

- The ETU monitors the valve body action, output flow, and output pressure of the SCM.
- It monitors the SCM's 16-way solenoid valve and the multichannel sensor information inside the SEM, inside the SCM, and outside the SCM.
- It has a fiber optic and power carrier redundant communication interface, which can realize the monitoring of the SCM.
- It has system functions such as user management, historical data, and self-diagnosis.

3 General Layout of Subsea Control Module Test System

The SCM test system consists of four parts: an HPU, an SCMTS, a signal generator, and an ETU. The working principle is illustrated in Figure 2.

Figure 2 Testing device

3.1 Design of Hydraulic Station

According to the design requirements, the hydraulic station must provide at least two high-voltage outputs, two low-voltage outputs, and one return oil pipeline (Hammond et al. 2018). The high-pressure output pressure and low-pressure output pressure can be adjusted through different pressure tests. The hydraulic system is designed to filter and output oil, and its key components are redundant. Moreover, it provides high cleansing pressure fluids and exhibits a stable structure. The pressurized oil output is adjustable, with a low-pressure oil pressure output of 34.5×10^6Pa and a high-pressure oil pressure output of 69 MPa.

The block diagram of the hydraulic system design of the hydraulic station is shown in Figure 3. The system includes redundant power unit-1, redundant filter unit-3 in series with redundant power unit-1, and two control branches. Redundant oil supply unit-2 and pressure monitoring-A are connected to the control circuit between redundant power unit-1 and redundant filter unit-3, respectively. The control branch includes two paths (How et al. 2010). One path is buck unit-4, emergency stop shutoff pressure relief unit-5 connected to buck unit-4, and pressure monitoring-C. The second path is buck unit-4', emergency shutoff pressure relief unit-5' connected to buck unit-4', and pressure monitor-C'. Whether or not redundant filter unit-3 is blocked can be determined by considering the difference between pressure monitoring-A and pressure monitoring-B. Then, we can decide if the system requires an emergency stop operation. The output pressure of the system can be monitored by pressure monitoring-C.

3.1.1 Redundant Power Unit

The redundant power unit is shown in Figure 4. The power unit can be used by running any pump, and the other pump is used as a backup. The program automatically runs the standby pump only when the main pump fails; the main pump is not always in operation. When the system is in operation, the pressurized oil accumulator is

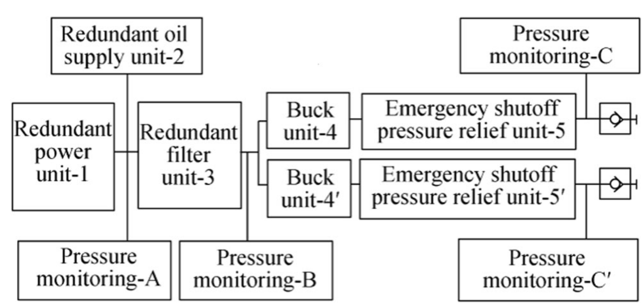

Figure 3 Block diagram of the hydraulic system design of the hydraulic station

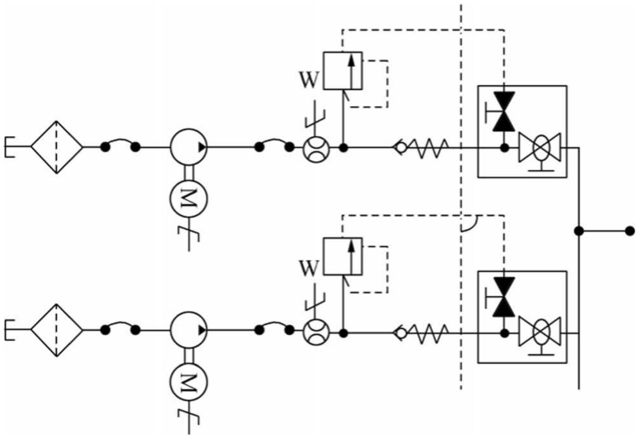

Figure 4 Redundant power unit

subject to the standard. When 52 MPa ≤ HP and 32 MPa ≤ LP, the high-voltage and low-voltage motors are automatically stopped, and the pump stops working. When HP ≤ 35 MPa and LP ≤ 21 MPa, the high-voltage motor and low-voltage motor start automatically, and the pump starts operating.

3.1.2 Redundant Oil Supply Unit

The redundant oil supply unit is shown in Figure 5. The advantage of this design is that when accumulator-1 fails, it can be replaced after the pressurized oil in accumulator-1 is completely discharged by closing the shutoff valve-1 and opening the unloading valve-1 (Sinha et al. 2007). In this process, accumulator-2 can still operate normally, thereby ensuring the normal operation of the entire system.

3.1.3 Redundant Filter Unit

The redundant filter unit is shown in Figure 6. In this system, the hydraulic fluid meets the accuracy requirement of 3 μm. Therefore, the fine filter in the hydraulic system is prone to clogging. If fine filter-1 is clogged, the operator can close shutoff valve-1 and shutoff valve-2 and then open unloading valve-1 and unloading valve-2. After the pressure in the line is reduced to zero, the operator replaces the filter element in fine filter-C.

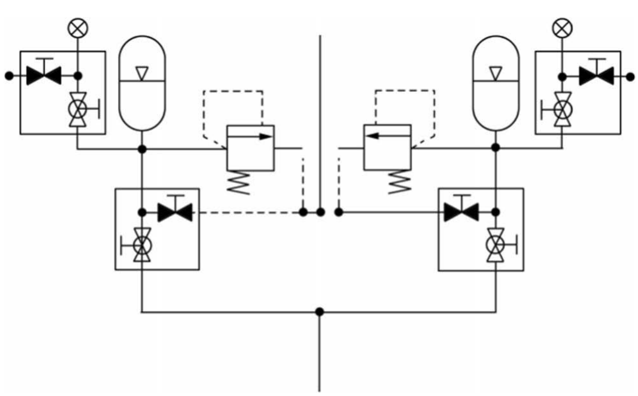

Figure 5 Redundant oil supply unit

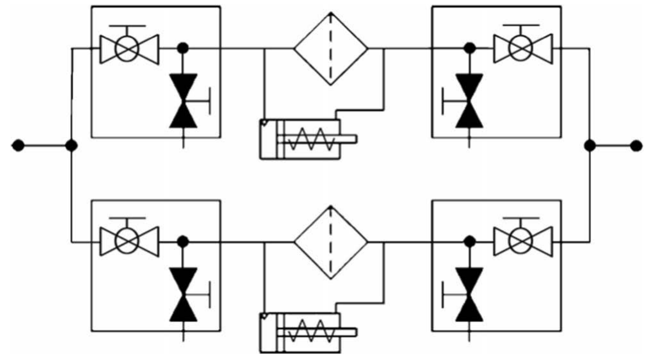

Figure 6 Redundant filter unit

3.1.4 Emergency Shutdown Pressure Relief Unit

The emergency shutdown pressure relief unit is shown in Figure 7. When the load runs normally, the two-position four-way solenoid valve is energized to move the spool downward. The pilot pressurized fluid enters the two-position four-way hydraulic valve through the solenoid valve and pushes its spool downward (Azam and Khan 2010). The hydraulic station begins to output the pressurized oil to the load. Under load emergency, the solenoid valve power supply should be cut off in time. Then, the solenoid valve spool moves upward under the action of the spring to shut off the pilot oil supplied to the hydraulic valve. Simultaneously, the pilot oil flows back to the oil tank, the hydraulic valve spool moves upward and thereby shuts off the oil supply to the load, and the load pressure oil flows back to the tank. The function of the manual reset button on the solenoid valve is to prevent misoperation (Lewis et al. 2012). After the emergency shutoff, the oil can be reloaded by pressing the reset button. The reason for using the solenoid and hydraulic valves in this design is as follows. If the solenoid valve is directly used on the main oil path, then

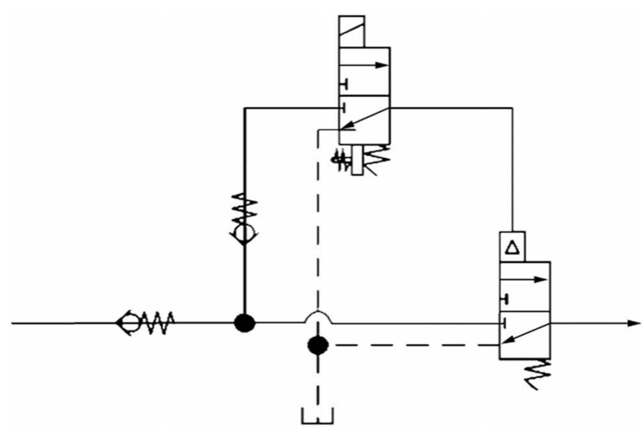

Figure 7 Emergency shutdown pressure relief unit

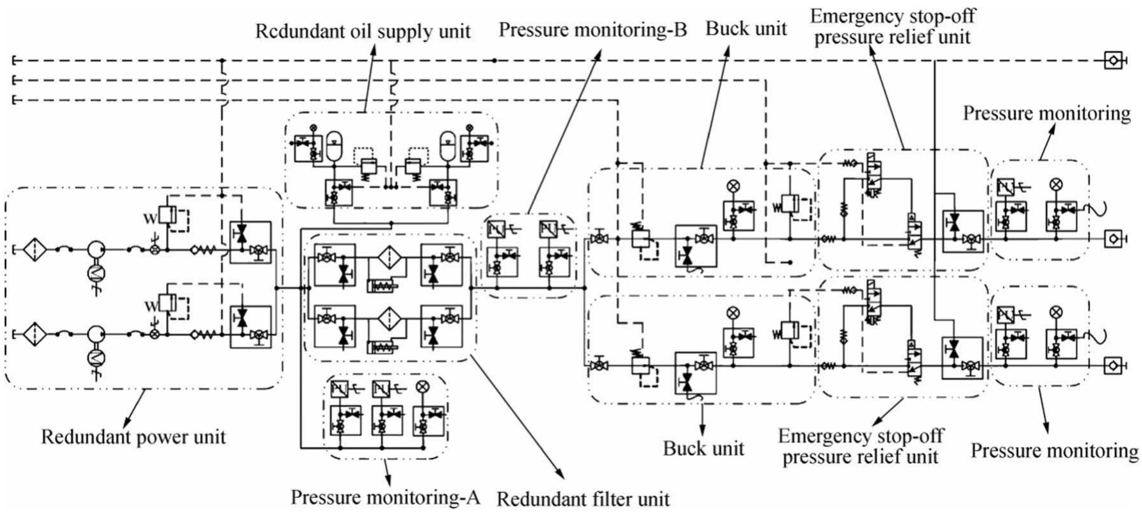

Figure 8 Schematic of hydraulic station hydraulics

the solenoid valve becomes excessively heated owing to the excessive driving force of the spool. This condition affects the service life and reliability of the hydraulic station.

The hydraulic system of the hydraulic station implements a redundant modular design; the hydraulic principle design of the hydraulic station is shown in Figure 8. The high-pressure hydraulic principle design is the same as the low-pressure hydraulic principle design. The difference lies in the hydraulic component parameters; therefore, Figure 8 only shows the hydraulic principle and does not distinguish between the high- and low-pressure designs (Nellessen 2010). During the test, only one motor and one pump are turned on to supply oil to the system; the other components are used as a backup power unit. The standby power unit operates only when the working power unit fails so that the system can continue operating normally without interruption. The advantage of such modularity is that when the hydraulic station fails, the faulty part can be directly isolated without affecting the normal use of the system.

3.2 Design of Test Stand

According to the design requirements, the test stand can be divided into two parts: the hydraulic system structure and the structural design (Christiansen et al. 2004). The overall design block diagram of the test stand is shown in Figure 9.

The high-pressure supply line and low-pressure supply line provide high-pressure oil supply and low-pressure oil supply to the SCM, respectively. The high-pressure function oil circuit and low-pressure function oil circuit are used to test whether the internal valves of the SCM are opened or closed, respectively. The panel layout is primarily intended to prevent any interference between the valve bodies on the rear panel. The docking station is designed to detect whether the docking device of the SCM docking station satisfies the design requirements.

The schematic representation of the hydraulics in the test stand is shown in Figure 10. HP1 and HP2 are the high-pressure redundant oil supply lines, and H1 and H2 are the high-pressure functional test lines (Fanailoo and Andreassen 2008). LP1 and LP2 are the low-voltage redundant oil supply lines, and L1–L14 are the low-pressure function test lines. HR is the high-pressure return line, and LR is the low-pressure return line. The pressurized oil from the hydraulic station enters the test stand from the quick connector. After the pressure is stabilized by the hydraulic gauge, the oil supply valve is opened to allow the pressurized oil to enter the load system. Typically, the shutoff valve is closed (Gupta 2010). The circuit shutoff valve is opened only when the oil return compensation function in the SCM is tested. The pressurized oil enters the SCM return system through a pressure reducing valve and check valve. To simulate the deep-water area, the oil return compensator makes the internal oil return system pressure the same as the external static water pressure.

The overall structural design of the test stand is shown in Figure 11. The docking station can simulate the SCM docking process and detect whether the locking device of the SCM docking station satisfies the design requirements (Shi et al. 2013). In the design process, the docking station is designed

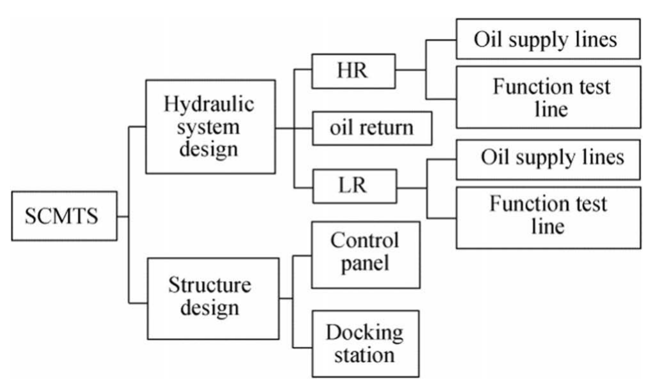

Figure 9 Overall design block diagram of the test stand

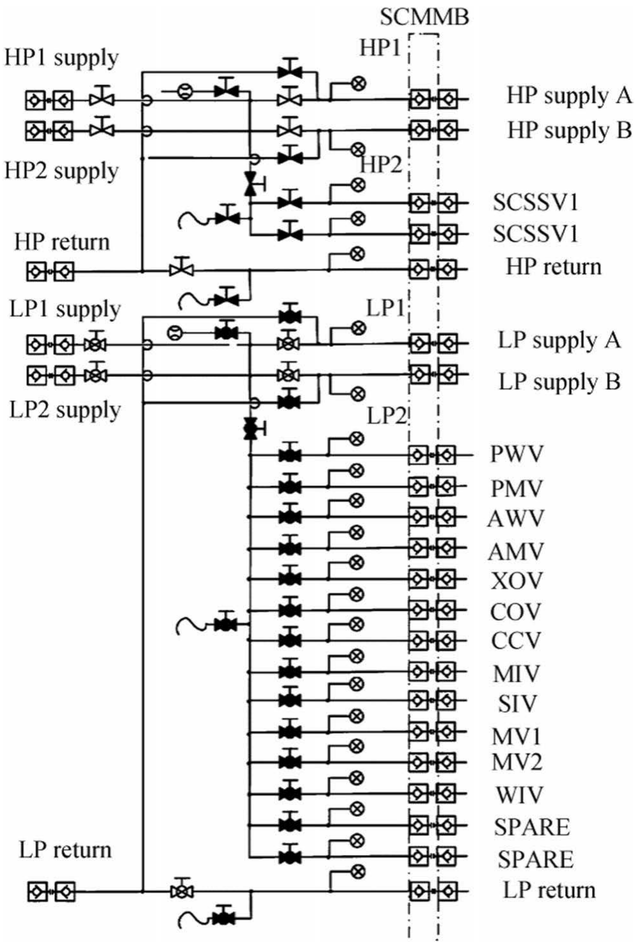

Figure 10 Hydraulic schematic of the test stand

with a replaceable form, along with the oil circuit configuration plate. During testing, the required hydraulic lines can be configured according to the different SCM test requirements to facilitate different SCM tests.

The design of the test control panel is shown in Figure 12. The back of the panel is the hydraulic line of the test station. The hydraulic components, such as the hydraulic gauges, operating hand valves, and oil sampling valves, are installed onto the front. The oil circuit switch is simulated with the hand

Figure 11 Structure of the test stand

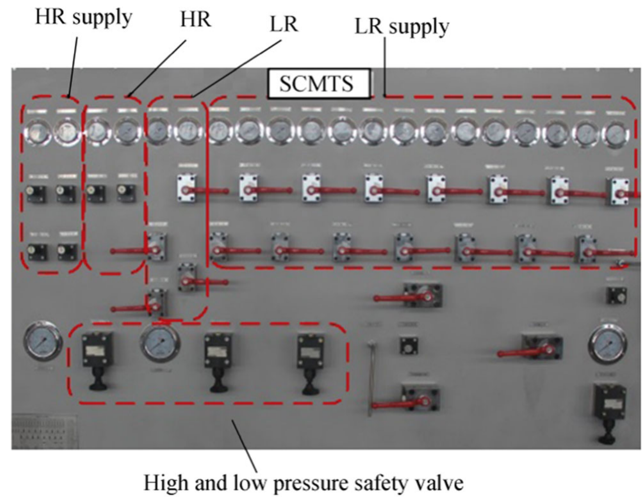

Figure 12 Design of test control panel

valve control switch. The hydraulic valve is used to determine whether the SCM internal valve is opened or closed according to the command.

3.3 Design of SGD

The SGD is mainly used to simulate the subsea sensing system and thereby send a corresponding analog signal to the SCM and detect whether the SCM can normally collect the monitoring signal returned by the subsea sensor.

The block diagram of the SGD program is shown in Figure 13. The commands shown in the figure are entered by the operator and transmitted to the central processing unit (CPU) module through an industrial computer. Then, the CPU module processes the input instructions. Finally, the CPU controls the digital module, analog module, and traffic module to send analog signals directly to the SCM (Tarcha et al. 2016). According to the type of signal emitted by the subsea sensor, the analog signal can be classified as a digital, analog,

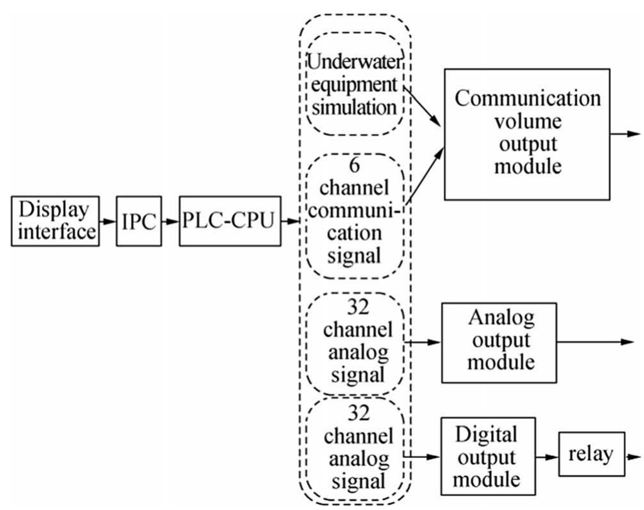

Figure 13 Block diagram of signal generator program

or traffic signal. All digital signals are indirectly output through the relay. The objective of this design is to avoid excessive PLC load. The four analog modules directly output eight analog signals to the SCM.

The program interface is designed to consist of five parts to facilitate the rapid learning of the design product by workers. The five parts are the user login bar, alarm status display bar, main menu (function selection bar), current control interface, and status bar.

During the subsea production process, the opening and closing states of the control valves in the subsea production equipment are fed back to the SCM as digital signals. Then, the SCM feeds back the acquired digital signal to the MCS, and the operator determines whether the corresponding valve has been opened or closed on the basis of the received information. According to the design requirements, the SGD can provide 40 digital signals, wherein the green color indicates the 24 V DC output voltage signal and gray color indicates the 0 V DC output signal. This interface can simulate digital signals, such as emergency shutdowns and the on/off status of valves (Wang and Chen 2014). The +/− button in the lower right corner of the interface allows the configuration of a number of channels for the digital signals to be accommodated by different SCMs.

The SCM collects signals containing information such as pressure and temperature. These signals are transmitted by various monitoring sensors installed onto the subsea production equipment. The SCM then transmits these signals to the MCS to allow the operator to control the underwater production in real time. According to the actual requirements, 32 analog signals of 4–20 mA can be simulated. The signal type, range, accuracy, and waveform can be individually set for any channel to facilitate the adaptation to different test objects. Clicking the channel number button corresponding to the analog operation module displays the signal trend graph of the channel in the lower part of the operation interface. This display facilitates the intuitive observation of the trend of analog signals.

The environmentally controlled temperature sensor, environmentally controlled pressure sensor, and nozzle position sensor installed onto the underwater production facility are fed back to the SCM by the communication signal and then transmitted to the MCS by the SCM. Each channel transmission uses a dual data design (Wen et al. 2011). Each type of data, such as the name, signal type (pressure, temperature, position, etc.), signal type (step, square wave, sine wave, etc.), amplitude, range, and accuracy, can be individually set on the interface. The signal trend graph of the channel at the lower part of the operation interface is displayed by clicking the corresponding channel number button.

In addition to the abovementioned configurable signal channels, the SGD is designed for underwater equipment simulation. Such application allows operators to intuitively understand the underwater production environment. The underwater equipment simulation includes underwater production equipment, such as Christmas trees, separators, and manifolds. Similarly, operators can set the temperature and pressure signals of the corresponding pipelines. They can also turn the simulation valve on or off to achieve the objective of simulating different signals in an actual working environment.

3.4 Design of ETU

During the test, the ETU is mainly responsible for issuing commands to the SEM in the SCM for opening or closing the solenoid valve in the SCM. Additionally, it can read the data in the SEM and receive the signals sent back by the SCM for monitoring the SCM and the underwater production environment (Yue et al. 2012). The hardware part mainly comprises an industrial computer, PLC, relay, and wiring terminal. The industrial computer is mainly responsible for running the ETU software. According to the actual conditions, the optical fiber module or power carrier module can be selected for data exchange between the ETU and the SCM.

The block diagram of the ETU program is shown in Figure 14. The command input by the operator on the display interface is transmitted to the CPU through the industrial computer. The CPU issues an instruction to open/close the valve or read the monitoring information and output the command to the SCM through the power carrier or network switch. Then, the parameters returned by the SCM are displayed in an operational or graphical manner.

The role of the ETU is equivalent to the role of the MCS in an actual task during the test. On the one hand, the ETU can test whether or not the SCM can transmit the collected signal back to the MCS and ensure that the signal is not distorted (Zhonglin 2013). On the other hand, the ETU can issue an action command to the SCM during the test and instruct whether to open or close the corresponding valve in the SCM to complete the SCM valve control. Additionally, it can monitor the signals and parameters inside and outside the SCM.

The main interface consists of five parts: user login bar, alarm display bar, main menu (function selection bar), current control interface, and status bar. Part of the action is similar to that in the SGD. However, the main menu of the ETU mainly

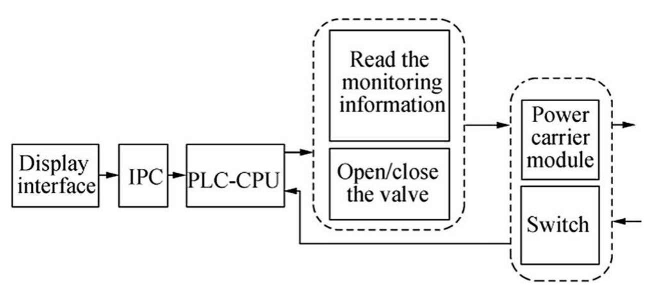

Figure 14 Block diagram of the ETU program

includes the SCM valve control, SCM internal monitoring, and SCM external monitoring.

In actual production, the correct opening or closing of the valve is the most important part of the entire underwater production system. Losing control of any valve can cause immeasurable damage to the production. The ETU can open and close the SCM valve. It can also test whether the valve wiring in the SCM is correct and whether it can be normally turned on or off according to the setting procedure. In addition, the valve must be opened or closed during subsequent tests, including the valve leakage test, sensor test, and so on. The ETU can control 16 SCM valves and simultaneously monitor the pressure and temperature signals corresponding to the 16-way valve body in this interface (Zhang et al. 2018). Clicking on any valve displays the corresponding status parameters mentioned below.

The ETU monitors all pressure, temperature, and flow signals inside the SCM in real time. The SCM internal monitoring interface can monitor 24 signals, including the low-pressure supply pressure, high-pressure supply pressure, low-pressure return pressure, high-pressure return pressure, SEM internal temperature, SEM internal pressure, low-pressure oil flow, high-pressure oil flow, and pressure and flow signals for 16-way valves. Each monitoring signal can simultaneously monitor its real-time value. To understand the signal trend, one can also click on the "Image" button. In this way, the staff can master the SCM work, identify and resolve problems promptly, and avoid further problems.

In subsea production systems, a large number of sensors are installed onto Christmas trees or other equipment. The monitored signal must be uploaded to the main control station through the SCM to ensure that the operator is aware of the production situation in the Christmas tree. In this design, the SCM external monitoring interface of the ETU can simultaneously monitor 20 signals, including the production pressure, production temperature, annulus pressure, annulus temperature, position of the Christmas tree valve, nozzle position, and nozzle pressure difference. For each monitoring signal, one can view the signal trend by clicking the "Image" button to display the trend graph.

4 SCM Test

As the core part of the composite electrohydraulic control system, the SCM has a long service life but is costly, difficult, and expensive to install and inconvenient to use in underwater maintenance. Therefore, it should be subjected to performance and functional tests prior to its launch to ensure its normal operation after watering (Zhu and Liu 2010). These tests also help avoid secondary installation and maintenance after the launch.

Hence, tests should be conducted to determine whether the valve body action in the SCM is normal and whether the SEM can normally collect and transmit the monitoring signal. These tests should also aid in determining whether the mechanical strength and function of the SCM can meet the usage requirements and whether the internal hydraulic system or compensation system can satisfy the design requirements. The image of the SCM of a composite subsea electrohydraulic system is shown in Figure 15.

The SCM test is mainly divided into the SEM test (including the SCM external analog signal acquisition and transmission test, SCM external digital signal acquisition and transmission test, and SCM external communication signal acquisition and transmission test), hydraulic system test (including the valve control test, reversing valve test, accumulator capacity and internal discharge test, PMV control valve failure safety test, and hydraulic system seal test), mechanical structure test (including the housing seal test and butt lock function test), and oil return compensation system and pressure compensation system test. The control test of the SCM valve and the internal monitoring of the SCM in the SEM test must be completed in the hydraulic system test. In the mechanical structure testing, the pressure joint testing in the hydraulic system test must be completed. Moreover, the oil return compensation test and pressure compensation test in the hydraulic system test must be carried out inside a high-pressure water tank. Despite the differences in the various SCM design standards, the main tests have the abovementioned four components.

The test considers the simulation of the Christmas tree as an example. Two high voltages and four low voltages are used.

After starting the hydraulic station, the pressure reducing valve in the operation panel of the hydraulic station is adjusted to set the output pressure to a high pressure of 34.5 MPa and low pressure of 20.7 MPa. Then, the high-pressure supply valve and low-pressure supply valve are opened in the SCMTS. After the high-pressure and low-pressure supply

Figure 15 SCM of the 10-m subsea electrohydraulic system

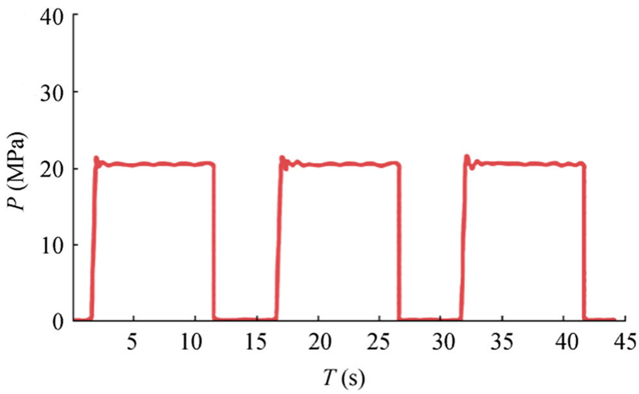

Figure 16 Trend curve of the opening pressure of the choke valve

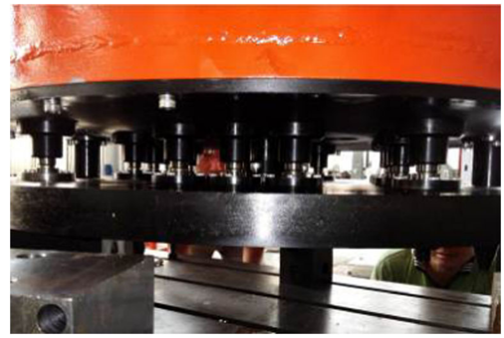

Figure 17 SCM after docking and locking

pressures are stabilized, the valves are successively opened using the SCM valve control interface in the ETU. Then, the pressure values of the two-way high-pressure function valve and four-way low-pressure function valve in the corresponding pressure gauge are observed.

The choke valve is switched three times in succession, and the corresponding pressure gauge value jumps three times. The pressure trend curve of the choke valve is shown in Figure 16. Upon the opening of the valve, small fluctuations occur and gradually stabilize. Finally, all valves are closed, and all functional oil pressure gauges of the SCMTS are observed. The pressure monitoring value and pressure trend curve of each valve are zero at the SCM valve control interface and SCM internal monitoring interface.

In the event of a fuel supply interruption, the accumulator in the SCM must maintain all underwater production equipment for 48 h of continuous operation. The internal leakage is directly related to whether the accumulator can satisfy the usage requirements. Therefore, the accumulator capacity must satisfy a minimum design value. Additionally, the internal discharge should satisfy a maximum design value. According to SCM performance parameters, the SCM leakage per minute should not exceed 0.2 cm^3/min, and the low pressure should not exceed 2.2 cm^3/min. In the actual investigation, the domestic SCM has a low-pressure leakage of 0.1 L/min and a high-pressure leakage of 0.5 L/min.

In the accumulator capacity test, the high- and low-voltage test methods are the same. Let us consider the low-pressure oil passage as an example. The LP1 and LP2 supply valves are closed in the test stand. The main circuit shutoff valve and return oil shutoff valve are closed. The PMV valve is opened by the ETU. Then, the test stand-merged channel sampling valve and PMV shutoff valve are opened. A sufficiently large measuring cylinder is placed at the sampling port of the confluence road until the PMV pressure gauge value drops to 0 MPa. The volume of oil recorded in the measuring cylinder is 5.8 L, which is greater than the minimum effective working volume of the low-pressure oil accumulator. Similarly, the capacity of the high-pressure oil accumulator can be measured as 1.2 L, which satisfies the design requirements.

In the internal discharge test, the high-pressure test and low-pressure test methods are the same. Let us consider high-pressure oil passages as an example. The oil in the low-pressure SCM system is drained, and the timing equipment is prepared in advance to prevent any interference. Then, only oil is supplied to the high-pressure SCM system. After the pressure stabilizes, the oil return valve is closed, and the oil return sampling valve is opened. After collecting the leaking oil for 10 min at the oil return sampling port, the volume of the oil in the measuring cylinder is 0.26 L, which is less than the specified standard. Similarly, the leakage of the low-pressure oil circuit can be measured as 0.04 L, which satisfies the usage requirements.

The underwater installation of the SCM requires underwater remote-operated vehicle assistance. Therefore, the requirements for the rotational torque and number of revolutions of the device must be strict. In this test, the locking device of the SCM docking station is designed to have a rotational torque of 1000 N m and maximum safe rotational torque of 2000 N m. During the test, the test stand should be able to supply pressurized oil in a normal manner.

The operator completely unlocks the upper and lower docking plates of the SCM, completely lifts the SCM with a crane, and then lowers the SCM with the crane. A torque wrench is used to apply the same torque to turn the drive mechanism of the locking mechanism until it cannot rotate. Then, the torque is increased to 1200 N m until the locking

Figure 18 Unlocked and separated SCM

Table 1 Summary of the SCM test results

Test content	Settings	Test results	
		Results	Errors
External communication signal acquisition and transmission test	PT1: 20 MPa	20.1 MPa	0.5%
	PT2: 15 MPa	15.05 MPa	0.33%
	TT1: 20 °C	19.8 °C	0.4%
	TT1: 15 °C	15.2 °C	1.33%
Valve control test	High pressure: 34.5 MPa	34.46 MPa 34.33 MPa	0.5%
	Low pressure: 20 MPa	19.83 MPa 19.89 MPa 19.95 MPa 19.92 MPa	0.85%

mechanism cannot be rotated. Figure 17 shows the SCM after the docking is completed. After several repetitions, the butt joint is not damaged, and oil does not leak during the locking and disengaging process. The locking function of the docking station satisfies the requirements. Figure 18 shows the SCM after unlocking and separating. The test results are summarized in Table 1.

5 Conclusion

This study investigated the SCM and its working environment to propose a set of testing schemes and develop a set of testing devices. The testing device consists of four parts: hydraulic station, test stand, SGD, and ETU. Four devices were designed according to the test requirements. The testing device was used to test the SCM. The following results were drawn from this study:

1) The high- and low-pressure oil output of the hydraulic station was stable and reliable, and the pressure was adjustable. Thus, the test requirements were satisfied.
2) The hydraulic system of the test stand was designed to satisfy the testing requirements for the SCM hydraulic system. It was also found to be capable of monitoring every pipeline.
3) The SGD could issue different analog signals according to the requirements.
4) The ETU could issue an operation command to the SCM and receive a monitoring signal returned by the SCM.
5) The joint SCM test was completed to verify the feasibility of the test methods and the effectiveness of the testing device.

Funding This study was supported by the National Key R&D Program of China (2018YFC0310500), High-Tech Ship Research Projects sponsored by the Ministry of Industry and Information Technology (2018GXB01) and Yantai City school land integration development project (2019XDRHXMPT29): research and development and test platform of underwater production system.

References

Abicht D, Braehler J (2010) Performance assessment of the DC all-electric subsea production control system. SPE Asia Pacific Oil and Gas Conference and Exhibition, Brisbane, 1–9. https://doi.org/10.2118/133439-MS

Altamiranda E, Kiaer L, Hu X (2009) OCEANS 2009 - Europe Conference, Bremen, GERMANY.999-+

Azam MA, Khan K (2010) Design of the Ethernet based process data extraction algorithm and storage technique for industrial HMI systems. The 2nd International Conference on Computer and Automation Engineering (ICCAE), 1, 551–553. https://doi.org/10.1109/iccae.2010.5451871

Bai Yong, Bai Qiang (2010) Subsea engineering handbook. Gulf Professional Publishing, 216–219

Chen B, Su F, Zhou K, Liu D, Liu H (2014) Test technology of subsea production system. Ocean Eng Equip Technol 1(2):146–150. https://doi.org/CNKI:SUN:HYZB.0.2014-02-014

Chen J, Hao G, Han L, Wang Z (2018) Subsea production system ESD0 test review for PanYu34-1 gas field. Mech Electr Eng Technol 47(11):78–80. https://doi.org/10.3969/j.issn.1009-9492.2018.11.024

Christiansen PE, McKay SA, Mullen K, Upston LR (2004) Remote field control and support strategy-umbilicals versus control buoys. SPE Asia Pacific Oil and Gas Conference and Exhibition, Perth, Australia. https://doi.org/10.2118/88546-ms

Da Cunha G, Rossa AJ, Alves JA, Cardoso E (2017) IEEE Trans Ind Appl 54(2):1899–1905. https://doi.org/10.1109/TIA.2017.2785764

Da Cunha G, Rossa AJ, Alves JA, Cardoso E (2018) Control of permanent magnet synchronous machines for subsea applications. IEEE Trans Ind Appl 54(2):1899–1905. https://doi.org/10.1109/tia.2017.2785764

Eriksson K (2011) Control system and condition monitoring for a subsea gas compressor pilot. Meas Control 44(7):208–211. https://doi.org/10.1177/002029401104400703

Fanailoo P, Andreassen G (2008) Improving reliability and reducing intervention costs of ultradeep subsea technology at the design stage. Offshore Technology Conference, Houston. https://doi.org/10.4043/19539-ms

Gardner B, Carter R (2005) Distributing the knowledge from the ocean: application of open standards in subsea control systems. Offshore Technology Conference, Houston. https://doi.org/10.4043/17327-ms

Gong H, Li J, Wang Y, Qu H (2014) Study on hydraulic system of test stand for subsea control module. Appl Mech Mater 548-549:1023–1029. https://doi.org/10.4028/www.scientific.net/amm.548-549.1023

Gupta P (2010) Over-speed limiter schemes for full authority digital engine control system. 2010 International Conference on Industrial Electronics, Control & Robotics, 164–168. https://doi.org/10.1109/iecr.2010.5720166

Hammond S, Osman H, Ismail L (2018) Integrated field performance study for subsea production control system. Offshore Technology Conference Asia, Kuala Lumpur, Malaysia. https://doi.org/10.4043/28516-ms

How BVE, Ge SS, Choo YS (2010) Dynamic load positioning for subsea installation via adaptive neural control. IEEE J Ocean Eng 35(2):366–375. https://doi.org/10.1109/JOE.2010.2041261

Lewis M, Money R, Kochenower C (2012) Subsea system, production controls and umbilicals for typhoon project. Offshore Technology Conference, Houston. https://doi.org/10.4043/14125-ms

Liang J, Yao B, Qu Y, Duan L, Shi J (2012) Review of testing technology for subsea production system. China Meas Test 38(1):38–40

Nellessen P (2010) SS: subsea well intervention: development of a deepwater subsea well intervention package control system. Houston. https://doi.org/10.4043/20438-ms

Shi H, Gong G, Yang H, Mei X (2013) Compliance of hydraulic system and its applications in thrust system design of shield tunneling machine. Sci China Technol Sci 56(9):2124–2131. https://doi.org/10.1007/s11431-013-5248-8

Sinha JK, Balla CBNS, Meher KK (2007) Early contact detection between two components. J Sound Vib 303(3-5):918–924. https://doi.org/10.1016/j.jsv.2007.02.012

Su F, Chen B, Zhang F, Zhou K, Liu D (2015) Subsea oil & gas production system underwater test facilty study. China Meas Test 41(7):6–9,15. https://doi.org/10.11857/j.issn.1674-5124.2015.07.002

Tarcha BA, Furtado RG, Borges OC, Vergara L, Watson AI, Harris GT (2016) Subsea ESP skid production system for Jubarte field. Offshore Technology Conference, Houston. https://doi.org/10.4043/27138-ms

Wang F, Chen Y (2014) Dynamic characteristics of pressure compensator in underwater hydraulic system. IEEE/ASME Trans Mechatron 19(2):777–787

Wen D, Wang Z, Guo J, Zhang Y, Lv S, Tetsuhiro T (2011) Output speed and flow of double-acting double-stator multi-pumps and multi-motors. J Zhejiang Univ-SCIIENCEA 12(4):301–309. https://doi.org/10.1631/jzus.a1000405

Yue Y, Zuo X, Wang L (2012) Reliability analysis of hydraulic directional control valve installed in subsea control module. Struct Saf Reliab:2. https://doi.org/10.1016/omae2012-83605

Zhang Lan, Li Yongzhe, Meng Yonghong, Wang Liquan, Peng Jia (2018) Installation and docking technology of control module for subsea production system. 2nd International Conference on Mechanical, Electronic, Control and Automation Engineering (MECAE 2018), Qingdao, China. https://doi.org/10.2991/mecae-18.2018.69

Zhonglin Z (2013) Design and research on the two-joint mating system of underwater vehicle. China Ocean Eng 27(1):111–120. https://doi.org/10.1007/s13344-013-0010-3

Zhu Yan, Liu Jingguang (2010) The adaptive control simulation of electro-hydraulic proportional system. 2010 International Conference on Computer, Control and Electronic Engineering, Changchun, China. https://doi.org/10.1109/cmce.2010.5610365