Underwater robot local dry welding system

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Received 21 July 2019; accepted 11 September 2019

Abstract To satisfy the demand for good quality underwater welding and maintenance of nuclear power stations, a set of local dry automatic welding systems has been developed. These systems were based on an underwater robot that consisted of a special high-power underwater welding power supply, diving wire feeder, mini drain cap, welding robot, and special underwater welding torch. With a digital signal controller microprocessor as its core and combined with a dual inverter topology, the welding power supply was characterized by full-digital construction and multi-waveform flexible output. A compact diving wire feeding device was designed, based on the armature voltage negative feedback and high-frequency chopping pulse width modulation.This device yielded a high-efficiency seal of the driving motor with the help of dynamic and static sealing technology. To overcome the difficulty of local protection and deslagging in the welding area, a mini drain cap (with a duplexgas structure) based on the principle of the convergent nozzle was designed. The practical tests and the underwater welding experiments revealed that the underwater robotic local dry welding system is quite feasible. That is, the system could strike the arc stably and reliably in the shallow water environment, and formed beautiful welding seams.

Key words local dry, underwater robotic welding, underwater welding power supply, mini drain cap, underwater wire feeder

0 Introduction

Completely eliminating the risk of nuclear accidents is impossible, because nuclear power stations are unable to withstand severe natural accidents that exceed the design limits. Accidents such as pool cracks, holes, and crevices could also occur. Performing repairs by means of underwater welding is an important method for emergency maintenance of nuclear power stations. However, underwater welding maintenance is quite difficult due to the strong radiation, poor visibility, and multiple influencing factors of reactor pools, reactor internals pools, and spent fuel pools[1]. Among the three existing underwater welding methods, the local dry method can approximate the dry welding effect by adopting a mini drain cap that displaces the small area of the welding position. This method combines the advantages of high weld quality realized by dry welding with the convenience of wet welding[2]and is, therefore quite suitable for the underwater welding maintenance environment[3]. The development of an underwater welding robot,which is suitable for the strong radiation environment of a nuclear power station, is essential for improving the emergency handling ability after design basis accidents and nuclear accidents.

In this work, a set of local dry underwater robot welding systems was developed with the aim of fulfilling the demand for underwater emergency welding maintenance of nuclear power stations.The systems consisted of a full-digital high-power welding power supply, a compact diving wire feeding device, a mini drain cap, a fault diagnosis system, and other supporting equipment. Process debugging and experimental studies were performed. The developed local dry underwater welding system operating with a robot and visual system, could adjust the welding path and welding parameters, depending on the different requirements. The system could also track (in real time) the arc behavior during the welding process. Furthermore, the system could perform the necessary adjustments in order to satisfy the weld-

Foundation item: This work was supported by the National Natural Science Foundation of China (Grant Numbers 51375173).

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doi: 10.12073/j.cw.20190721002

ing requirements, eventually fulfilling the demand for emergency maintenance of nuclear power stations.

1 General scheme design of underwater welding system

The developed underwater robot local dry welding system was mainly composed of an underwater welding power supply, a diving wire feeder device, a mini drain cap and a special underwater torch[4]. Other components included a trackless mobile robot, a test tank, a welding quality analyzer, a remote monitoring computer, an underwater visual system, and a gas supply system. A schematic of the proposed welding system is shown in Fig. 1.

An underwater panoramic camera was used for coarse location of the area to be welded, and a binocular visual system was used for precise measurements of the position coordinates[5]. These systems provided basic data for the welding path planning of the trackless mobile robot. The underwater welding power supply was connected to the remote operating terminal via the controller area network (CAN). Therefore, the status and running process could be remotely monitored and controlled in accordance with the user-defined communication protocol. The power supply and mobile robot could achieve cooperative control through two separate switch signals.The trackless robot carrying the welding torch arrived at the starting point of the welding process, then output a signal and waited for a response. After receiving the signal, the power supply discharged the shielding gas, drainage gas, and filler wire successively. Furthermore, after the normal arcing process, a switch signal was output by the supply for feed back to the robot, and the robot would conduct the welding task in accordance with the planned path. The visibility of the arc in the local dry welding process was very poor. Thus, in order to monitor the stability of the welding process in real time and evaluate the welding process quality indirectly, computer aided monitoring and quality analysis of the welding process was conducted. During this evaluation, an electrical signal sensor was used to collect the real-time welding current and voltage, and a welding quality analyzer was used for real-time on-line monitoring and digital recording. A fault self-diagnostic alarm system was used for real-time monitoring and fault diagnosis of the welding process status information, and thus, the site running reliability was further improved.

2 Design of the special underwater welding power supply

2.1 Hardware design of the underwater welding power supply

In the work, MIG welding was employed. An underwater welding arc is quite complex. Therefore, high requirements for the performance of the underwater welding power supply (compared with those of other types of welding power supplies) were proposed for achieving reliable arcing and steady arc burning. A special underwater welding power supply of 630 A rated current with full-digital dual inverter construction was designed. The overall framework of the welding power supply is shown in Fig. 2.

The main circuit of the welding power supply consisted mainly of an EMI module, a three-phase rectifier filter module, a full-bridge inverter module, an intermediate fre-

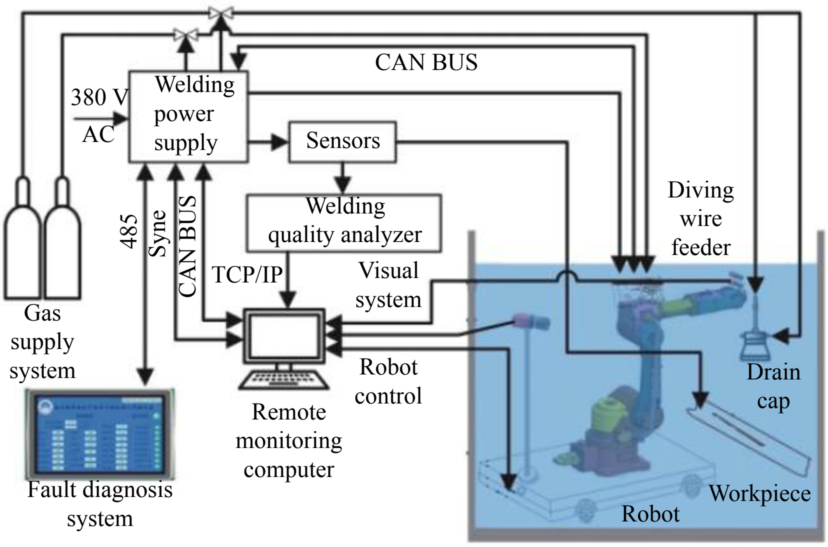

Fig. 1 Schematic of the proposed welding system

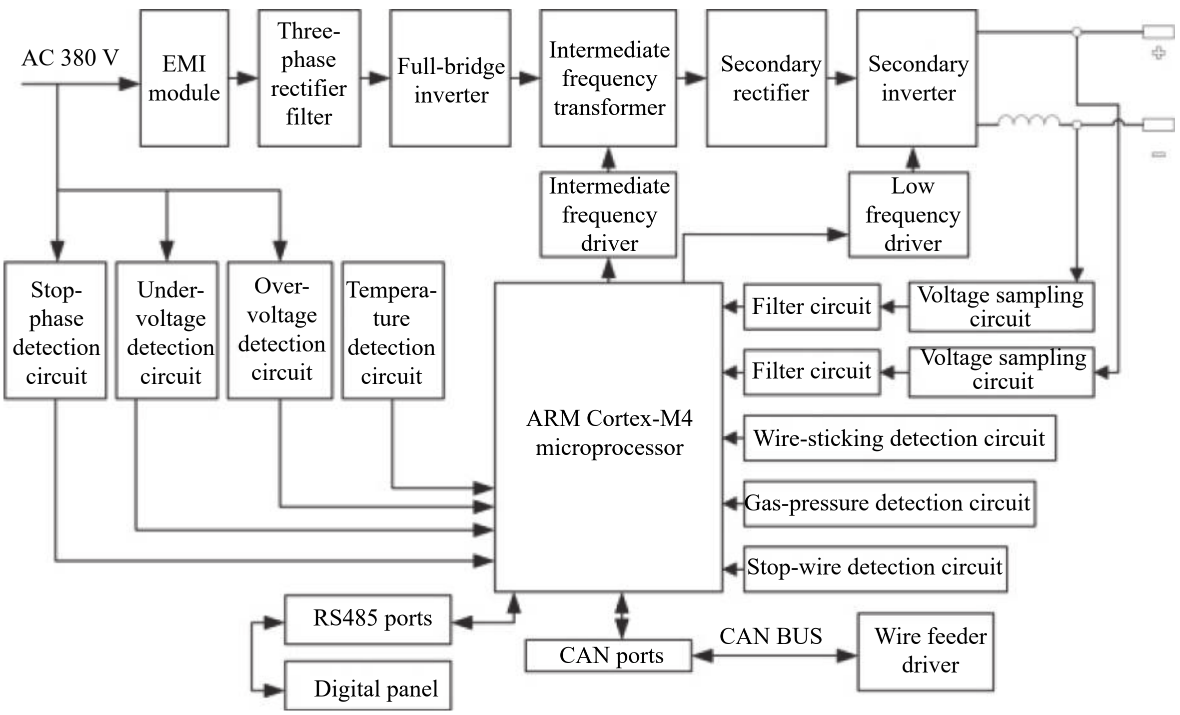

Fig. 2 **Overall framework of the welding power supply**

quency transformer module, a secondary rectifier module, and a secondary inverter module. A mature full-bridge topology was employed for the primary inverter and a dual half-bridge parallel structure was used for the secondary inverter to achieve increased power output and full power-margin utilization, respectively. To improve the quality of the output waveform by inhibiting the surge current, safety capacitors, high permeability cores, and power resistors were used to filter the common mode and differential mode noise. Power relays and power resistors were used to limit the impact of welding-current transient changes on the power grid. The control system adopted full-digital control technology, which was based on a DSC microprocessor with an ARM Cortex-M4 core. This system could work in constant current mode, constant voltage mode, equal power mode, and variable polarity mode depending on the arc characteristics in different stages. Furthermore, the system could output various characteristic waveforms such as pulsed waveform with a middle median or backward median phase, AC square waveform, pulse square waveform, constant current and constant voltage waveform. The control system was equipped with two separate CAN ports and RS485 ports. A special switch signal port was used to achieve synchronous control with the trackless robot.

2.2 Controller selection of the underwater welding power supply

The controller of the underwater welding power supply must perform significant amount of data processing and numerous synchronization tasks. Communication in real time with a remote monitoring computer and human-computer interactive fault diagnosis system is also required. Thus, chip selection of the controller is crucial. In this work, a STM micro-electronics DSC micro-processor with an ARM Cortex-M4 core was used, and this core was characterized by good performance and various communication ports. This micro-processor issues special DSP commands and is equipped with a float point unit (FPU),with the data processing ability of 210DMIPS, numerous IO ports for communication, analog signal acquisition, switching signal processing, and signal output control. As shown in Fig. 2, a double closed-loop control strategy was adopted for the welding power supply. The voltage filter circuit conducted KRC low-pass filtering for the feedback voltage signal with a cut-off frequency of 50 kHz. Therefore, a high-frequency ripple was filtered and signals were modulated to ensure that the microprocessor could accurately follow the output voltage of the welding power supply. A similar approach was adopted for the current feedback circuit.

2.3 Controlling software design of the underwater welding power supply

For multi-tasking real-time scheduling and high efficiency running, a Free-RTOS embedded real-time operation system was implanted into the DSC microprocessor. The corresponding drivers for the hardware were developed on the basis of the firmware library in the Keil MDK-ARM development environment.Pulse width modulation (PWM) signals were generated by timing the counter output comparison mode of the microprocessor, and were then expanded, isolated, and amplified to drive IGBT. A 12-bit successive approximation AD converter was used to acquire the feedback current and voltage signal, and a sliding window was designed for noise reduction of the input data. In addition, for remote monitoring of the welding power supply, a fault self-diagnostic alarm program and a CAN bus communication processing program were also designed for data communication with a remote monitoring host computer.

Process control software flow of the welding power supply was designed, based on the above mentioned factors[6]. A mature discrete PID control algorithm was used to process the feedback current and voltage signal as well as generate PWM signals with corresponding duty ratio to control the full-bridge inverter module. Consequently, a closed control loop was formed. Moreover, based on the given processing parameters of the digital panel, the DSC microprocessor modulated the sequence of given values and corresponding output low-frequency PWM signals. This was aimed at controlling the working mode of the secondary inverting bridge, and eventually a waveform with corresponding frequency, amplitude, and characteristics was obtained.

2.4 Fault diagnosis system of underwater welding

Various faults can occur during the running and welding process of the underwater welding robot system and, hence, a fault diagnosis system was designed (Fig. 3). This system consisted mainly of: hardware modules (e.g., temperature detection circuit, stop-phase detection circuit, under-voltage detection circuit, over-voltage detection circuit, gas-pressure detection circuit, wire-sticking detection circuit, stop-wire detection circuit, welding torch collision detection circuit,and human-computer interface based on touch screen).Other system components included software modules, corresponding to the hardware modules, and a data communication module.The fault diagnosis system could take measures such as human-computer interface alarming, passing information to other equipment or starting self-protection, depending on the type and emergency degree of the fault. The system communicated with the welding power supply by means of an RS485. From the human-computer interface, we could directly set process parameters and determine the running status and fault information,which could be displayed synchronously via communication with the remote monitoring host computer.

Fig. 3 Interface of the fault diagnosis system.

3 Design of the diving wire feeder

During the emergency welding maintenance process of an underwater robot used for a nuclear power station, the wire feeder is exposed to an intensely radiated and deionized water environment. A compact diving wire feeding device was designed (Fig. 4). The pressure difference between the internal and external motor and deceleration device of the diving wire feeder was larger than that of the regular wire feeder. Therefore, the dynamic sealing technology and static sealing technology for driving shaft rotation and preventing water penetration of the motor, respectively,

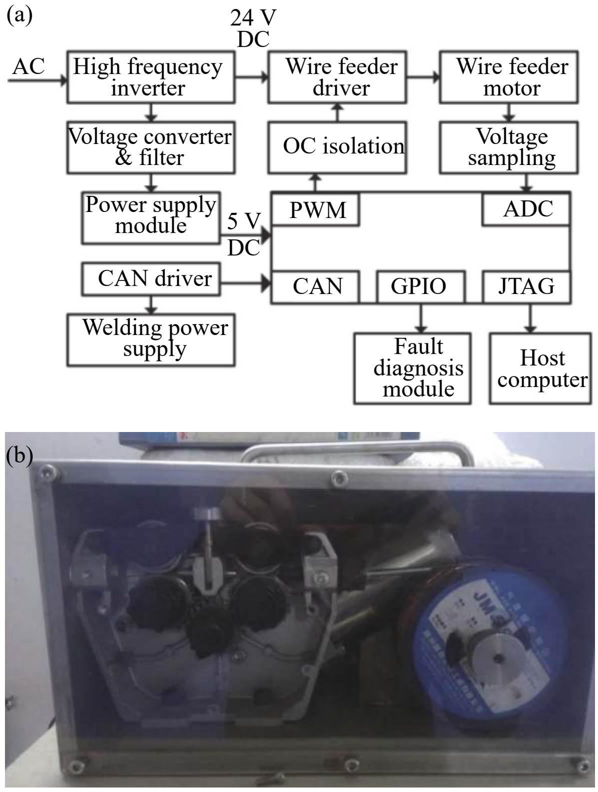

Fig. 4 Diving wire feeder (a) Principle diagram of wire feeder driver (b) Photograph of wire feeder

are key components of an underwater wire feeding device. In this work, for applications occurring at water depths of up to 50 m, the locally sealed diving wire feeder was designed using dynamic and static sealing technology. The driving motor was the only locally sealed component, and other components (e.g., the wire reel)were immersed in the water and, hence, the weight and volume of the wire feeder were quite low.

To guarantee the stability and precision of wire feeding, a digital driver was designed for the wire feeder by integrating DSC digital control, armature voltage negative feedback, and high frequency chopping pulse width modulation. This driver could achieve precise and step-less adjustment of the wire feeding speed. The developed diving wire feeder worked well underwater, and the effect of feeding resistance variation (resulting from status change of the feeding hose) on the wire feeding speed was <3% [7]. The diving wire feeder communicating digitally with the welding power supply by CAN, thus further improved the given precision and the anti-interference ability of the transfer process.

4 Design of the mini drain cap

A mini drain cap is the key component of an underwater robot local dry welding system[4].The design feasibility of the cap will directly determine the stability and drainage effectiveness of the local gas-phase area and consequently affect the stability of the welding process and weld formation.

Considering the difficulty of local protection and deslagging in the welding area, a mini drain cap (with a duplex gas structure) based on the principle of the convergent nozzle was designed (Fig. 5). The structure diagram and a photo of the cap are shown in Fig. 5a and Fig. 5b, respectively. The high-temperature protection cover outside the cap adhered to the workpiece during the welding process. This led to the formation of a relatively enclosed space, thereby ensuring the stability of the gas flow in the cap and resulting in an improved isolation effect. The drain cap consisted of two gas channels. Direct intake was adopted mainly for protection of the welding arc and the molten metal area by the internal shielding gas. A multichannel tangential spiral intake was used for the outer drainage gas [8].Through the recompression effect of the convergent nozzle, the high-speed and high-pressure gas would be accelerated,leading to the formation of a high-pressure rotating gas. On the one hand, the rotating gas could forcibly drain the water in the drain cap, resulting in the formation of a local dry space, which enabled local dry welding. On the other hand, vortices were formed in the central zone of the rotating gas (i.e., the welding arc zone). The relatively low pressure of the vortex center was beneficial for reducing the negative effect of the water depth on the welding arc zone. The high-temperature protection cover adhered to the workpiece and, hence, dust and slag would be generated during the welding process. Therefore, for effective deslagging, a buffer zone for the dust and a method for preventing falling of the slag into the weld seam zone were designed. The buffered dust was discharged with the shielding gas along the gap between the drain cap and the workpiece. According to previous studies, the caps with this type of convergent nozzle structure exhibited strong adaptability, thereby ensuring the stability of the gas phase in the welding zone and, consequently, the underwater welding quality.

5 Experimental results and analysis

In this work, an underwater local dry robot welding platform was established by integrating a robot, an underwater welding power supply, a diving wire feeder, a drain cap, and otherresources. A local dry welding experiment was

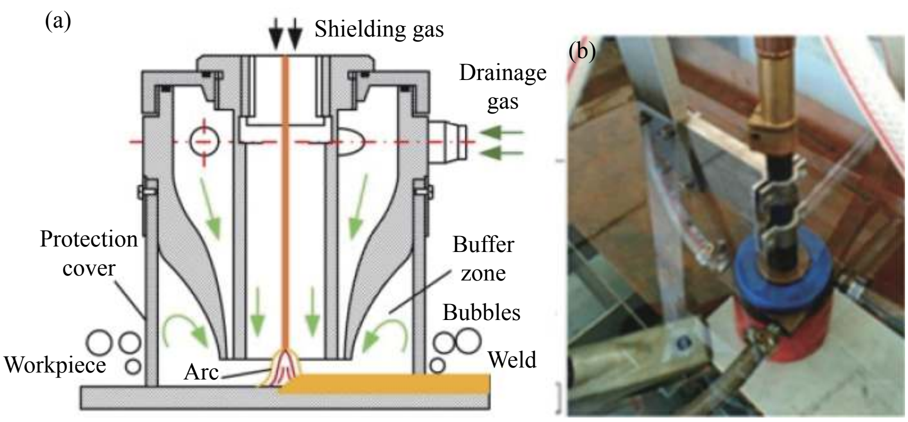

Fig. 5 Structure diagram and photo of mini drain cap(a) Structure diagram(b) Photo of mini drain cap

performed in the shallow water (water depth: 0.3 m). The thickness of the 304 stainless steelworkpiece and the diameter of the filler wire were 4 mm and 1.2 mm, respectively, and MIG welding was adopted. The actual weld seams are shown in Fig. 6. Gas with relatively high pressure should be bubbled into the mini drain cap to form a highly stable gas phase area during the underwater welding process. The arc pressure may have increased due to this high gas pressure. The average voltage and the average current were 28 V and 173 A, respectively, during the welding experiment. Compared with the pressure corresponding to land welding, a higher arc pressure under the same condition indicated that greater input energy was required. Furthermore, the actual weld appearance revealed a sound weld seam with a smooth surface, the absence of defects such as pores, slags, and cracks,and a few spatters.This indicated that the weld meets the requirements of underwater emergency welding maintenance for nuclear power stations.

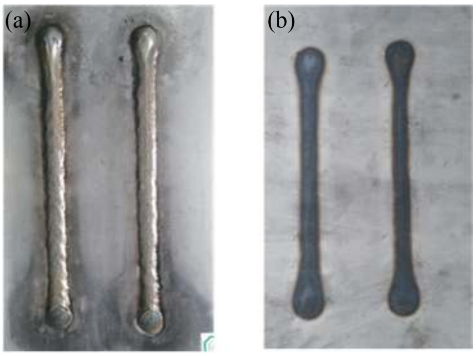

Fig. 6 Photograph of welding seam obtained by means of the local dry method(a)Weld face appearance(b)Weld backside appearance

6 Conclusions

(1) The developed underwater robot local dry welding system could meet the special demand of underwater local dry welding. The developed welding power supply could work stably and reliably with a rapid response speed. The specially designed control strategy could adapt well to the characteristics of the underwater arc.

(2) The mini drain cap (with a duplex gas structure) based on the principle of the convergent nozzle could overcome the difficulty of local protection and deslagging of the welding area during the underwater welding process.

(3) The local sealed diving wire feeder was characterized by a reasonable dynamic and static sealing design, compact structure, rapid response speed for wire feeding, stability, and reliability.

(4) The developed local dry underwater robot welding system could achieve a stable welding process, uniform weld joints without porosity, high deposition rate, and sound weld appearance.

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