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Research Article

Design of submarine pipeline inspection system based on ultrasound

Ding Bingbing*, **Zhang Sen and Yan Yuemin**

College of Mechanical and Electrical Engineering, Binzhou University, Binzhou, China

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Abstract

A design of a non-destructive testing system for underwater pipelines based on ultrasound has been proposed, consisting of a three-axis control system and an ultrasonic thickness measurement system. This can achieve full coverage testing and real-time data transmission of pipeline wall thickness through integrated composite rotating mechanisms, travel driving mechanisms, pipeline surface preprocessing mechanisms, data acquisition systems, etc., with high automation and the ability to achieve pipeline based testing. Among them, the pipeline surface pretreatment mechanism includes a polishing mechanism and a circulating immersion system, which are used to improve the coupling effect between the pipeline wall and the ultrasonic probe. This non-destructive testing system can achieve high detection efficiency and testing accuracy, effectively solving the current problems of undersea pipeline leakage and inaccurate positioning of corrosion damage. At present, the problem of global and efficient scanning still needs to be solved, as otherwise it will be difficult to further improve work efficiency.

1. Introduction

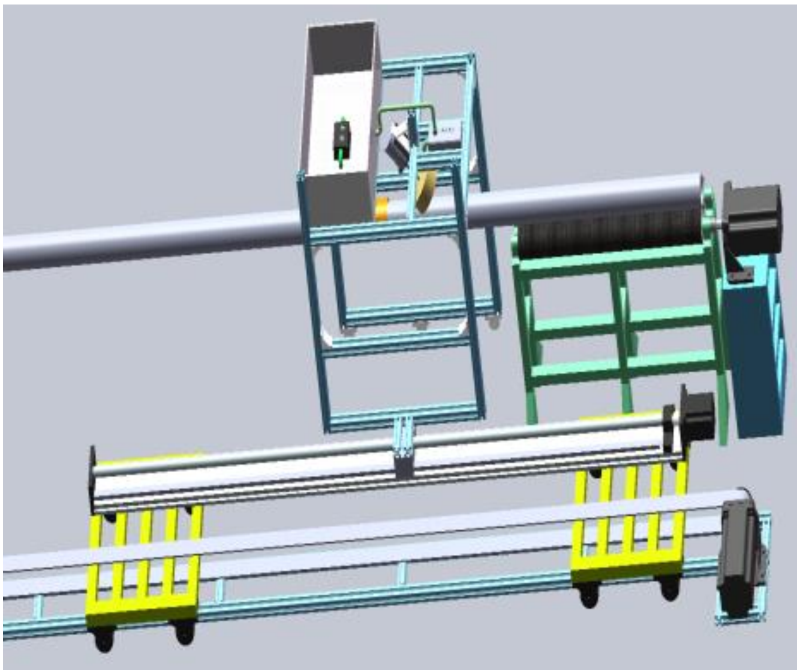
Ultrasonic testing has shown good application results in various fields of engineering (Miyamoto et al., 2023; Rabe et al., 2023). Under the friction of high-pressure media, the inner surface of submarine pipelines is prone to corrosion, local eccentric wear, and other issues. When the inner wall coating falls off or ages, the problem of pipe wall damage will significantly intensify, causing pipeline leakage and seriously affecting the safety and reliability of supporting equipment. At present, common methods for detecting oil production pipelines have obvious shortcomings. For example, high-pressure damage detection may be missed due to critical pressure issues. Fixed point non-destructive testing is suitable for spot checks and cannot accurately locate the amount or location of corrosion damage. In response to the above issues, this project is based on ultrasonic sensing technology to design a fully covered non-destructive testing system for oil production pipelines (Aleshin et al., 2022; Kim et al., 2023). It can not only achieve regular and comprehensive detection of pipeline inner wall damage or corrosion, but also achieve efficient and automated operation, solving problems such as missed inspections and inaccurate damage positioning (Ang et al., 2023). This detection scheme is not affected by the adhesive or coating materials on the inner wall of the pipeline, and has significant economic and market benefits.

*Corresponding author: College of Mechanical and Electrical Engineering, Binzhou University, Binzhou, China
E-mail address: zxin900@126.com

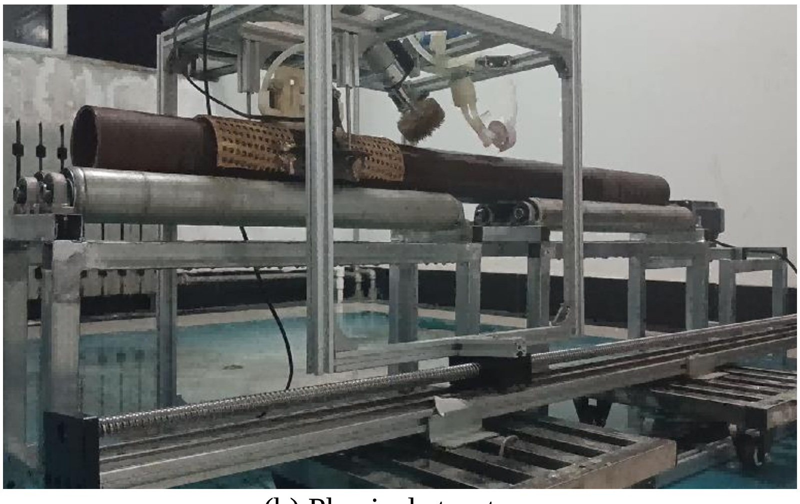
2. Overall system design and implementation plan

2.1 Framework design

The overall structure of the non-destructive testing system for submarine pipelines is shown in **Figure 1**, consisting of the HJ40L triaxial control system and an ultrasonic thickness measurement system. It can achieve real-time detection and wireless transmission of pipeline thickness through integrated composite rotating mechanisms, travel driving mechanisms, pipeline surface pretreatment mechanisms, data acquisition systems, etc. It is a new type of pipeline non-destructive testing equipment. The entire detection actuator has four degrees of freedom; among them, the composite rotating mechanism includes multiple drum groups, which drive the drum to connect the motor. Combined with the motor connected by the screw module, it can achieve the spiral motion of the ultrasonic probe relative to the pipe wall. The pipeline surface pretreatment mechanism includes a polishing mechanism and a circulating immersion system, which are used for effective coupling of pipeline wall cleaning and ultrasonic probes.



(a) Designed structure

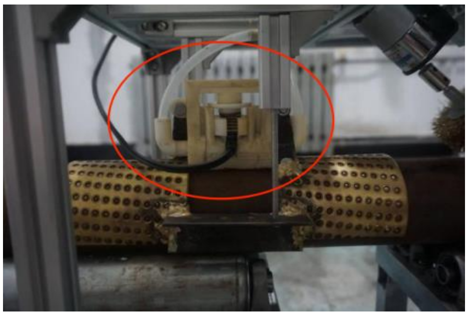


(b) Physical structure

Figure 1 Overall structure of the non-destructive testing system for oil production pipes.

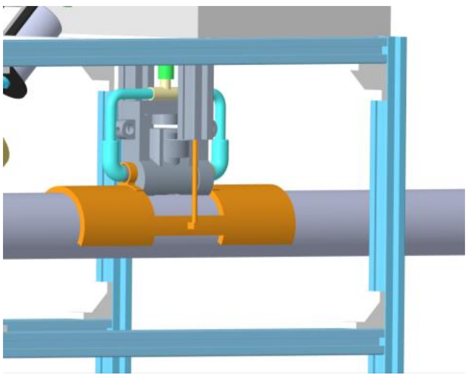
2.2 Main flaw detection mechanism

Due to the fact that the testing environment for pipelines is mainly at room temperature and atmospheric pressure, there is no need for temperature or pressure parameter compensation, but specific support mechanisms need to be used to maintain stable rotation. The main flaw detection mechanism, as shown in **Figure 2**, is installed above the radial guide mechanism and consists of three parts: an ultrasonic thickness measurement system, an ultrasonic probe, and a coupling mechanism. Among them, the ultrasonic thickness measurement system is fixed on the top of the machine frame, facilitating on-site parameter adjustment, data reading, and wireless data transmission. The surface of the ultrasonic probe is wrapped in a water condensation film, which can emit four ultrasonic signals per second, with a sampling frequency of 4 Hz. The coupling mechanism is fixed on the auxiliary motion mechanism and is divided into upper and lower layers. The pressure between the ultrasonic probe and the pipe wall is controlled by the elastic force of the spring. Due to the complex internal structure, the coupling mechanism is prepared using 3D printing technology, with circulating constant temperature water flowing on both sides to ensure good coupling between the probe and the pipe wall during non-destructive testing work. The ultrasonic thickness measurement system can load real-time data into a PC computer through a Bluetooth serial port or USB interface, facilitating subsequent data processing.



(a) Coupling mechanism

(b) Radial guide mechanism



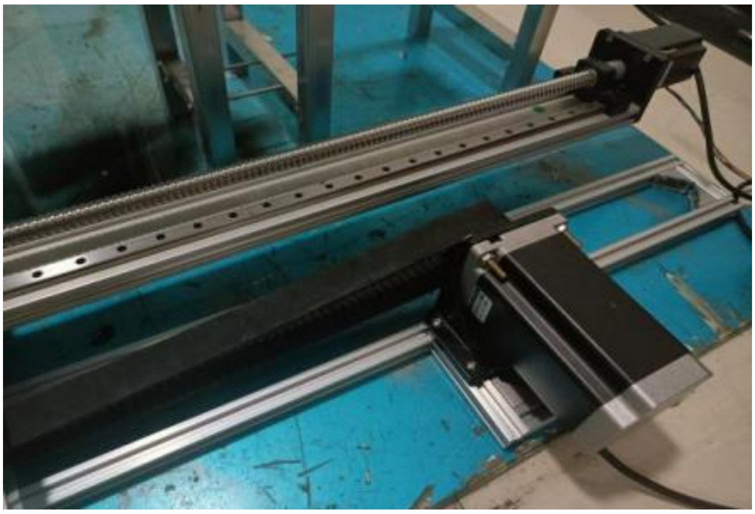
(c) Coupling and radial guide rail assembly model

Figure 2 Main flaw detection mechanism.

2.3 Design of motion control mechanism

The motion control mechanism includes a rotating motion mechanism (as shown in **Figure 3a**), a local linear feed mechanism (as shown in **Figure 3b**), a global linear feed mechanism (as shown in **Figure 3c**), and a guide mechanism (as shown in **Figure 3d**), driving the final assembly model as shown in **Figure 3e**. The rotating motion mechanism is composed of a servo motor, a coupling, a rubber wrapping drum, and a regular drum. A servo motor with a torque of 12 Newton meter is connected to a coupling, which is connected to a rubber drum to drive the rubber drum to rotate. The rubber drum drives the oil pipeline to rotate through friction, while also driving three ordinary drums to rotate. The local linear feed mechanism is composed of a ball screw system, a support frame, etc. It can perform radial fine adjustment motion on the basis of the global linear feed mechanism, making it easy to accurately locate and locate pipeline damage locations. The global linear feed mechanism consists of a servo motor, synchronous pulley, synchronous belt, trolley, and guide rail. A part of the synchronous belt is fixed on the trolley, which can slide along the guide rail. Above the trolley is the screw fixed on the trolley and the entire machine frame. The motor drives the trolley along the guide rail through synchronous pulleys and synchronous belts, achieving automation of the entire pipeline inspection.

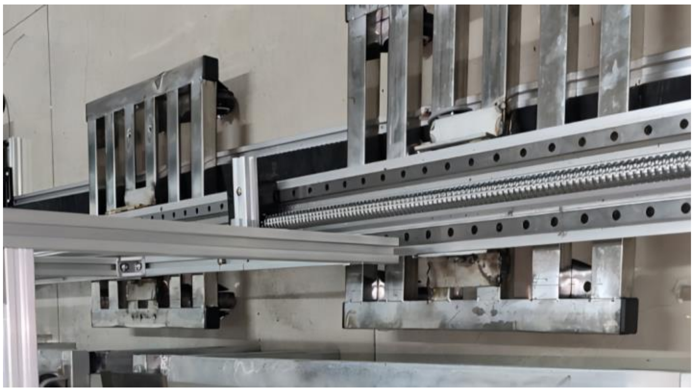
(a) Rotating motion mechanism



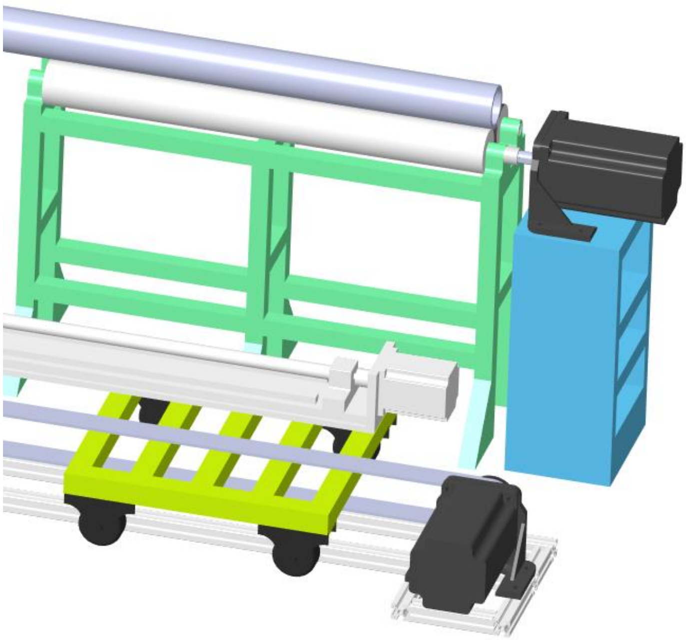
(b) Local linear feed mechanism

Figure 3 Structure and composition of motion control mechanism.

(c) Global linear feed mechanism



(d) Guide mechanism

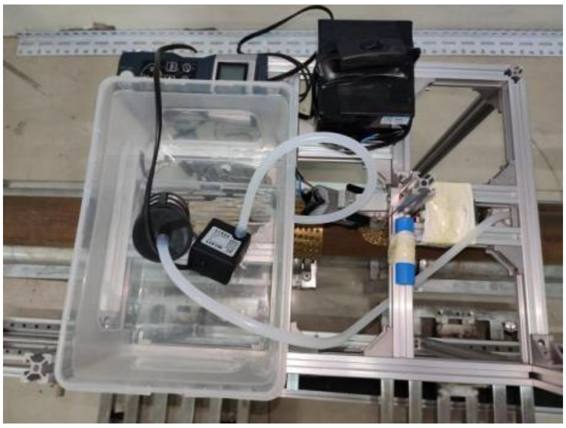


(e) Drive assembly model

Figure 3 (continued) Structure and composition of motion control mechanism.

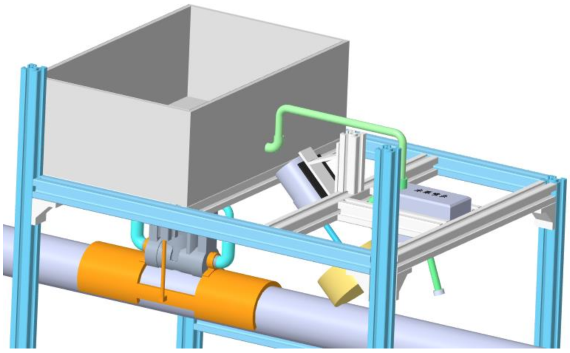
2.4 Design of pre-treatment mechanism

The pre-treatment mechanism (as shown in **Figure 4**) consists of a water tank, a water pump, a circulating immersion mechanism, and a dust removal mechanism. Each pre-treatment mechanism is fixed on the overall frame of the machine. The function of the circulating immersion mechanism is to pre-wet the pipe wall, ensure a stable water film thickness, wash away easily falling debris, and provide a stable medium for the coupling between the probe and the pipe wall; the dust removal mechanism is set in front of the probe, and its function is to polish the pipe wall, remove rust and debris that are not easy to fall off, and improve the flatness of the outer surface of the pipeline. The main function of the water tanks and pumps is to provide water sources for the circulating water immersion mechanism and flaw detection mechanism.



(a) Immersion mechanism

(b) Dust removal mechanism



(c) Assembly model of pre-treatment mechanism

Figure 4 Structure and composition of the preprocessing mechanism.

Figure 5 Servo system control panel.

Figure 6 Ultrasonic parameter setting panel.

2.5 Control system design

The control system consists of controllers, drivers, encoders, sensors, etc., and is mainly designed through programming to achieve unified control of different motors. The angle and speed of each motor can be manually adjusted, or can be automatically achieved through programming. The servo system control panel is shown in **Figure 5**. Through controller programming, the three main motors are operated according to the program, including drum rotation, radial movement of the main flaw detection structure, etc., so that the flaw detection system collects data from the entire pipe wall in the form of a spiral line. By using this method of replacing the surface with a line and densifying the points into a line, the numerical value of the pipe wall is measured. Where there are data defects, the lead screw can be used to drive the flaw detection system to refine the testing path again, facilitating precise flaw detection. The measured data will be synchronously displayed on the thickness measurement system and PC end. The setting panel for ultrasonic testing parameters is shown in **Figure 6**. After initialization and correction, error compensation can be set based on environmental temperature, humidity, etc. Before measuring the workpiece, the operator should preset its sound velocity based on the type of material or measure the sound velocity based on the standard block. When using one material to calibrate the instrument (a commonly used test block is steel) and then measuring another material, incorrect results will be generated. It is required to correctly identify the material and select the appropriate sound speed before measurement. For the selection of measurement schemes, the system includes standard measurement mode, maximum measurement mode, minimum measurement mode, difference measurement mode, average measurement mode, and other working modes.

3. Optimization and function expansion of system testing parameters

3.1 Optimization of parameters

The twin crystal probe consists of two independent crystals separated by soundproofing materials. These two crystals form a certain angle, so when one crystal emits an ultrasonic pulse, it enters the material through the ultrasonic coupling agent, hits the back wall of the material, and echoes back to the other crystal, receiving it. The ultrasonic thickness gauge uses pulse velocity and the time required to propagate from one crystal to another to calculate the thickness of the material. The soundproofing material prevents any sound from directly reaching the receiver from the transmitter before the pulse completes its path. The ultrasonic thickness gauge requires parameter calibration of the zero point. After adjusting the sound speed to 5,900 m/s, the operator presses the ZERO key to enter calibration mode. When the standard sample shows 4mm, the calibration can be completed.

Firstly, experimental research was conducted on the thickness measurement effect of detection coils with different numbers of winding coils. The test block material was carbon steel, with a thickness of 30 mm. Comparing the detection results of 20, 40, and 80 coils, it was observed that, when using a 20 coil to detect a 30 mm thick carbon steel test block, only one bottom reflection signal was observed at a gain of 61.5 dB. When using a 40 coil to detect a 30 mm thick test block, the first and second bottom reflection signals can be clearly observed at a gain of 54 dB. When using an 80 coil, the first to fourth bottom reflection wave signals can be clearly observed at a gain of 48.7 dB. The above results indicate that, when the number of winding coils in the detection coil is increased, it is equivalent to increasing the coil area, and the ability to transmit and receive signals is stronger, which is conducive to achieving the detection of larger thickness test blocks. At the same time, when the number of coils increases to 80, the outer diameter of the coil is already close to 30 mm, which is equivalent to the outer diameter of the permanent magnet used in this study. Continuing to increase the number of coil coils will cause the diameter of the coil to exceed the outer diameter of the permanent magnet. Therefore, this study ultimately chose the number of 80 coil coils as the optimized coil parameter.

When optimizing the magnetic field strength using a detection coil with a diameter of 0.2 mm and 80 coils, and conduct thickness testing on carbon steel test blocks with a thickness range of 25 - 80 mm, it was observed that, with a gain setting of 50 dB, for a 25 mm thick carbon steel sample, the waveforms of the bottom reflected waves were clear, the amplitudes were high, and the thickness measurement results were accurate. For the measurement of 50 and 80 mm thick carbon steel samples, with a gain setting of 55 dB, the waveform and amplitude of the first and second reflected waves on the bottom surface of the sample met the thickness measurement requirements, and the measurement results were accurate. When measuring a 50 mm thick sample, interference noise appeared at the 100 mm position, which may have been caused by the eddy current signal generated on the surface of the permanent magnet and the ultrasonic wave generated by the static bias magnetic field inside the permanent magnet. As shown in **Figure 7**, the thickness measurement results were obtained using a permanent magnet assembled from three small cylinders. It was observed that, under the same gain conditions, the amplitude of the reflected waves from the bottom of three cylindrical spliced permanent magnets was lower than that of seven cylindrical spliced permanent magnets. This indicates that a higher bias magnetic field intensity is beneficial for improving the energy conversion efficiency of the probe.

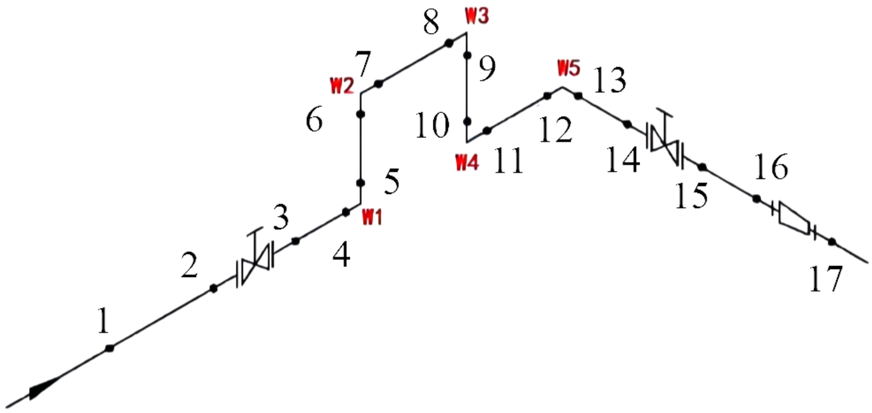


Figure 7 Thickness measurement results.

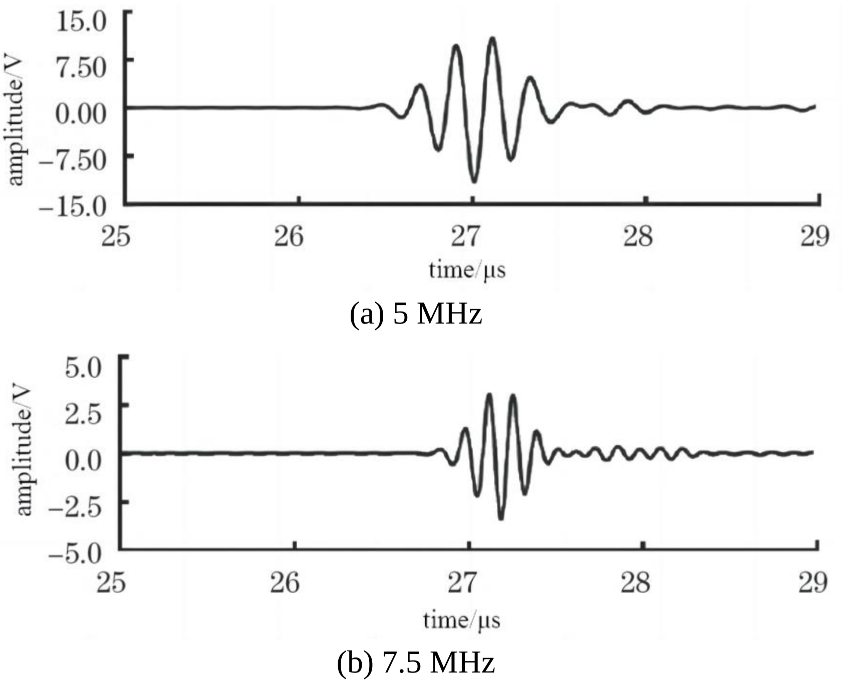


Figure 8 Refracted waves at different frequencies.

3.2 Functional expansion of stress detection

After being affected by stress, submarine pipelines can cause changes in the propagation speed of ultrasonic waves inside the material. The speed is influenced by the wavelength of ultrasonic waves, propagation direction, and internal stress of the material. The wavelength and waveform of ultrasonic incidence are controllable. After controlling the incident wavelength, waveform, and propagation direction, the change in residual stress can be obtained by simply measuring the change in ultrasonic propagation speed within the material. When the transmitting transducer excites the ultrasonic longitudinal wave to obliquely impact on the surface of the tested workpiece at the first critical angle, according to Snell's law, the ultrasonic critical refracted longitudinal wave can be generated inside the material of the tested workpiece and can be received by the receiving transducer, as shown in **Figure 8**. According to the principle of acoustic ejection, residual stress in materials can affect the propagation speed of ultrasonic longitudinal waves. When the direction of residual stress is consistent with the direction of longitudinal waves, tensile stress slows down the propagation speed or prolongs the propagation time of ultrasonic longitudinal waves, while compressive stress accelerates or shortens the propagation speed or time of ultrasonic waves.

4. Conclusions

A reasonable non-destructive testing scheme for submarine pipelines has been proposed in the paper, which can provide full coverage quantitative testing and accurately obtain the damage location and amount (wall thickness) of a pipeline inner wall in real-time. A pipeline detection mechanism is designed with a multi-degree of freedom structure. The detection cycle for a 10 m pipeline is less than 8 minutes, and each mechanism can automatically run according to the program, completely separating the detection process from manual intervention. The system can effectively eliminate the interference of pipeline temperature, humidity, internal adhesion, coating, etc., on wall thickness data, with a measurement accuracy of no less than 0.05 mm, achieving batch inspection of pipelines. Due to the use of an ultrasonic online detection scheme, it is not affected by the attachment of objects on the inner wall of the pipeline, has higher reliability compared to laser detection, X-ray imaging, magnetic flux leakage detection, and other methods, and has a lower equipment cost. A constant pressure sleeve structure is used to achieve close contact between the probe and the pipe wall, with a pre-immersion device and polishing mechanism, without the need for applying organic coupling agents. This not only greatly saves detection costs, but also enables efficient automated detection without being affected by manual detection errors. The forward and backward movements of the main structure are completed in the guide groove, so the overall operation is stable, with very little noise or vibration. In addition, fiber optic sensing technology has been a hot research topic in recent years, as its advantages, such as anti-interference and fast transmission, have made it widely used in various detection fields. However, the main problem is insufficient sensitivity, which is greatly affected by fluctuations in light source intensity and changes in connector losses. It can be seen that, with the development of this technology, there is hope that it will become an important pipeline corrosion detection scheme in the future.

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