Development of new pipeline maintenance system for repairing early-built offshore oil pipelines

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Abstract – **This paper introduces a set of new pipeline maintenance system for early-built long-distance offshore oil pipelines. An on-line intelligent inspection pig is developed using ultrasonic tool to detect defects in oil pipelines and the acquired data is stored for off-line analysis. Through analysing the data, defects can be found, sized, classed, and besides, the plan to locating them is made. An autonomous pipeline robot is developed to carry out the locating defects tusk, which adopts the way of detecting girth welds, combined with odometer wheels to locate the defects' position, so the problem of locating defects in early-built offshore pipelines unequipped with magnetic markers is solved. The paper introduces major components of the intelligent inspection pig and the autonomous pipeline robot and describes the process of maintaining offshore oil pipelines with the developed system.**

Index Terms – **Intelligent pig, ultrasonic inspection, locating defects, autonomous pipeline robot**

I. INTRODUCTION

It is generally accepted that high pressure pipelines provide the most efficient and safest means to transport large quantities of oil and natural gas. In China, lots of oil pipelines were buried in the continental shelf of Bohai Sea bay from 1970-1980. The region's physiognomy is complex and seabed under ocean wave's erosion is unsteady. So the oil pipelines exposed to a variety of environmental influences and loading conditions have run over 30 years. As a result flaws can appear and grow. Consequently, the pipelines are in the phase of frequently occurring leakage. In order to eliminating lost production costs and reducing pipeline downtime, the long-distance oil transmission pipelines under seabed need periodic inspection and the flaws and defects detected in the steel must be sized, located and repaired in time to insure safe run. An on-line intelligent inspection pig for detecting defects in oil transmission pipelines has been developed. The inspection pig with ultrasonic tools carries out the pipeline inspection tusk while it is at operating pressure. This enables pipelines inspection without reducing pipeline pressure or suspend the entire pipeline system. The inspected signals transferred from the ultrasonic tools are digitized, compressed by data processors to a manageable amount and stored in hard disk for off-line analysis. Through analyzing the data from ultrasonic inspection process, the pipelines having occurred anomalies such as dents and metal loss can be found, then the plan to locating and maintaining them could be made.

Lately-built long-distance offshore pipelines are equipped with magnetic markers which are buried at a certain distance and indicate the pipeline's rough position. The distance between two adjacent Magnetic markers can be measured by odometers. So for existing intelligent pig systems, magnetic markers combined with odometers are widely adopted to locate the defects in the pipeline [1][2], while early-built offshore pipelines weren't equipped with magnetic markers since the business of maintenance in future wasn't taken into consideration then, so the difficult of maintaining early-built offshore pipelines arises. An autonomous pipeline robot is developed to achieve the locating defects tusk, which adopts the way of detecting girth welds combined with odometer wheels to locate the defects' position, so the problem of locating defects in early offshore pipelines unequipped with magnetic markers is solved. Obviously, the girth welds of offshore pipelines play the role of magnetic markers for the new pipeline maintenance method. In this paper, major components of the intelligent inspection pig and the autonomous pipeline robot are introduced and the process of maintaining offshore oil pipelines with the system developed is described.

II. ON-LINE ULTRASONIC INTELLIGENT INSPECTION PIG

Magnetic and ultrasonic methods are the most commonly used to detect metal loss and cracking of pipelines. The major advantage of ultrasonic method is the ability, unlike magnetic flux leakage method, to provide quantitative measurements such as extension and depth of the defects with the precision of mm. Drawback is the need for a liquid couplant [3][4]. The oil transmitted plays the role of couplant, so ultrasonic inspection technology was the ideal choice.

A. Framework design of the intelligent inspection pig based on ultrasonic method

The ultrasonic intelligent inspection pig includes five components: liquid driver, system controller, power supply, ultrasonic inspection tool, and ultrasonic data processor. Figure 1 shows the intelligent inspection pig's architecture and table I shows its technical specifications. The five components are connected with knuckle-joint. Each component's mechanical part except liquid driver includes a cylindrical airtight cabin supported by supporting wheels. The airtight cabin is allowed to rotate freely around its longitudinal axis and supporting wheels keep the cabins

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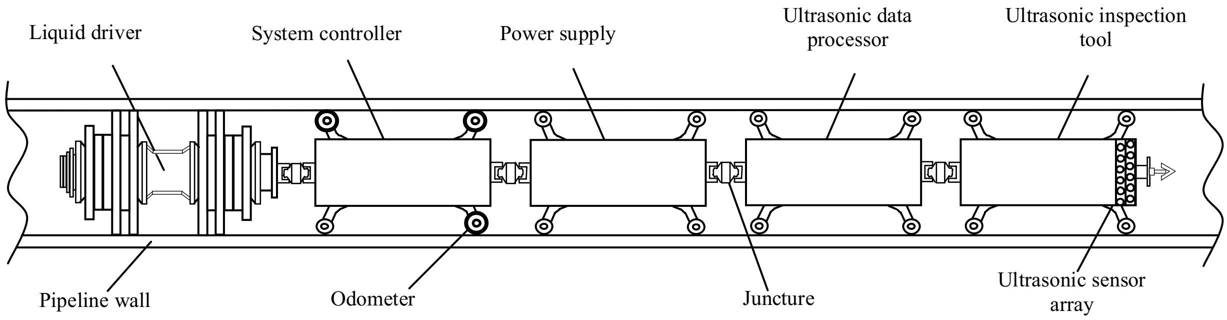

Fig. 1. Structure of Ultrasonic Intelligent Inspection Pig

centered in the pipeline. Inside the capsules are the ultrasonic transducers, eddy current sensor, environmental sensors, batteries and electronic devices. The electronics include PC/104 plus microcomputer, hard disk and data acquiring boards. The four cylindrical cabins are also connected by airproof hosepipes that electric power cable and data transmission wire lies in.

The liquid transmitted by pipelines drives the inspection pig train, the speed of which is determined by the transmission pressure. Experiments show the inspection pig train can move at the speed of about 150mm/s under 2MPa water pressure. Obviously, the faster the movement speed is, the higher the liquid pressure is. The power supply can provide electric power for the pig's electronic devices running over 40 hours.

TABLE I MAIN TECHNICAL SPECIFICATIONS OF THE INTELLIGENT INSPECTION PIG

Specification	Data
Number of bodies	5
Pipeline length inspected by once	≥20Km
Adaptive pipeline inner diameter	Φ195mm~Φ297mm
Minimum bend radius	3D
Inspection speed	≥0.5Km/h
Minimum eroded area detected	$10\times10mm^2$
Measurement error of pipe's thickness	0.5mm
Maximum pressure	4Mpa
Temperature of transmission medium	5◎—60◎

B. Ultrasonic inspection tool

Figure 2 shows the ultrasonic inspection tool that contains 64 ultrasonic transducers which work in time sequence, one eddy current sensor and several environmental sensors. All these transducers are divided into two groups with 32 transducers for each group and regularly staggered to ensure full circumferential coverage of the pipe. They are fixed on specially developed, highly flexible sensor carriers made of polyurethane to ensure that the stand-off and the transmission angle of the transducers are maintained during the inspection.

The ultrasonic transducers work in a pulse-echo mode with a rather high repetition frequency. For wall thickness detection, the distance between the transducer and the pipe wall can be obtained from the signal reflected by the pipe inner wall, and is used to evaluate the internal corrosion. The time of flight between the echoes from the inner and the outer wall is related to the pipe thickness and allows evaluation of the external corrosion [5]. Besides the 64 ultrasonic transducers, one humidity sensor, one temperature sensor and one pressure sensor are also fixed in this tool to collect the working environmental data of the transducers, which is used to compensate for the acquired ultrasonic scan data, later. The eddy current sensor is used to detect girth welds which need be identified instantly and play a pivotal role in the locating defects process. Conclusions are made from experiments shown in Figure 3, that girth welds can be instantly identified 100% when the ultrasonic inspection tool's movement speed exceeds 50mm/s in pipelines.

Fig. 2. High resolution ultrasonic on-line inspection tool for Φ195~Φ297 pipelines

C. Ultrasonic data processor

In this component, the ultrasonic scan analog outputs transferred from the ultrasonic inspection tool are AD-converted, compressed by data processors and stored in hard disk. In the process of data compression, arithmetic coding and HUFFMAN coding are adopted and the data compression percentage is 30% without any distortion. The ultrasonic data and odometer data transferred from system controller are stored with uniform time. The stored data can also be directly uploaded into a desktop or laptop PC for visualization or off-line analysis.

III. OFF-LINE DATA ANALYSIS AND DEFECT ASSESSMENT

The ultrasonic data from inspection process are firstly

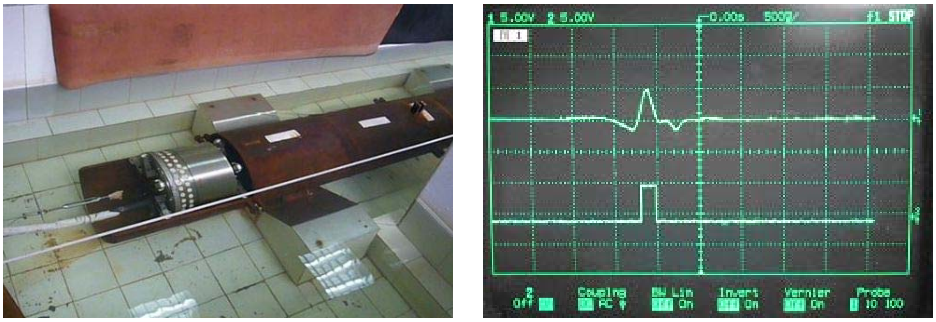

Fig. 3. The left picture shows girth welds' identification experiment in lab. The right screenshot shows a pulse generate when passing a girth weld

decompressed and then compensated by environmental data using wavelet theory. To speed up the data analysis work, the method that analyst combined with software tool identifies defects and girth welds from the mass data is adopted. A wavelet neural network will extract defect characters such as length, width and depth and achieve automatic defect findings according to the characters. This can reduce the number of defect candidates to be manually checked. A girth weld list can be easily got for its obvious characters by the software tool. Subsequently, the analyst will check up the defect candidates through the display of their data and draw conclusions. Figure 4 shows how data analysts look through the data to find defects or verify automatic defect findings. The identification of defects is mainly done by looking at several nearby A-Scans and C-Scan at one time. The viewing software will display the C-Scan of transducers that are circumferentially aligned. Defect signals show up in the A-Scans and defect images show up in the C-Scan clearly.

Defect assessment aims to describe the severity that a certain flaw represents for the safe operation of the pipeline. Generally speaking, a pressure is calculated that would still allow a safe operation of the pipeline considering the reduced strength of the flawed material [6]. For corrosion-like defects, the widely adopted assessment method is a straight one, for which input data are the length, width and depth of defects generally and output is permitted pressure. The calculation equation based on fracture mechanics computing method and elastic limit computing method for the permitted inner pressure is introduced in the Ref. [7]. For crack-like defects, the assessment method-BS7910 is adopted, which simplify a crack as a semielliptical shaped flaw [8]. Then, the permissible stress for the cracks can be calculated according to the simplified profile dimensions. In the end, seasoned analysts assess which level a certain defect belongs to by combining defects' dimension characters with calculated permissible stress.

A defect's level is labeled by A, B, C, D and E which is the most serious grade. Serial number of the pipes which defects lie in can be got by girth weld list and the C-Scan image which are marked by uniform time, while distance between the defect and the pipe's first girth weld can be got by the odometers' record data. So the defect's position in pipelines is

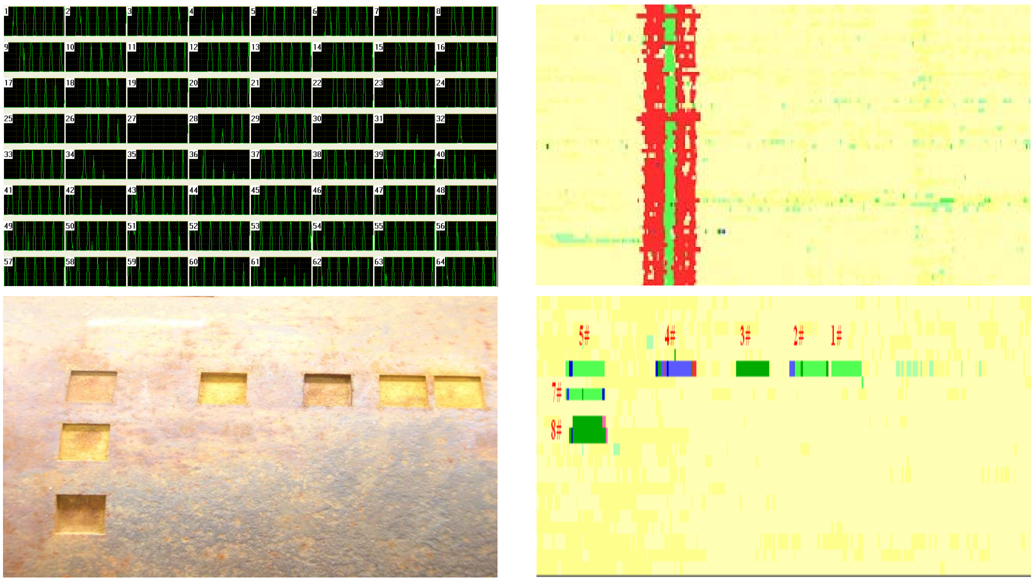

Fig. 4. The screenshots show different views on the ultrasonic data used by the analyst. The A-Scan (upper left) shows the recorded data from 64 transducers in one scan period. The C-Scan (upper right) shows a girth weld image. The picture (lower left) shows five different man-made defects outside the pipeline. The screenshot (lower right) shows the C-Scan image corresponding to the left man-made defects.

known and the precision determined by odometer wheels is 90mm. Through the off-line data analysis process, the file is got which records the pipeline defects' information and provides basis for the autonomous pipeline robot's achieving on-line locating defects tusk.

IV. ON-LINE LOCATION PROCESS WITH AUTONOMOUS PIPELINE ROBOT

The early equipment of the intelligent pig used isotopes for tracking the pig train and locating the defects. The restriction in use of isotopes, combined with their limited capability of locating precision, led to the development of an autonomous pipeline robot equipped with Ultra Low Frequency (ULF) electromagnetic wave emitter. The ULF signal has the characteristic to penetrate through metal pipe, bed load and seawater [9]. In the project, ULF electromagnetic wave performs the through-shield unidirectional wireless communication function. The autonomous pipeline robot has the similar structure to the inspection pig shown in figure 1. The differences are that the liquid driver is replaced by electric crawler and motor actuator, ULF emitter is added which is also placed in cylindrical airtight cabin and the power supply includes four cabins for increased electric power. The mentioned ULF emitter carries batteries as emergency power in case of power supply failure. The proposed electric crawler has six wheeled driving arms fixed circumferentially with 60° apart on the body frame. The driving wheels are located directly on the end of driving arms and can be controlled by single motor respectively, which forms the driving mode of six independent wheels. It features with compact structure, great transmission efficiency and big tractive forces [10]. The electric crawler equipped with mechanism of changing contour diameter adapts to pipeline inner diameter Φ195~Φ297.

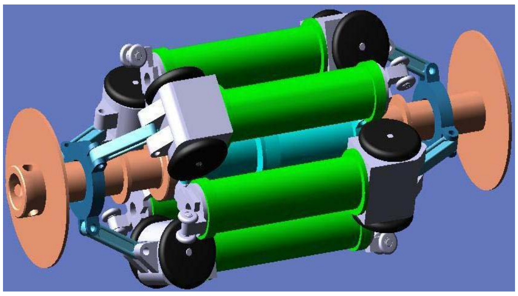

Fig. 5. Mechanical model of the electric crawler

A. *Tracking and locating defects*

The autonomous pipeline robot carries out the locating detects tusk on condition that the pipeline is operating, while the operating pressure isn't as high as normal one. There are four reasons for the action that liquid buoyancy effect lightens the location pig's weight and therefore increases the location pig's journey with the same carried electric energy, the low-pressure liquid flow pushes the location pig to increase the journey, while it doesn't affect the pig's suspension needed sometimes in the pipeline, another pipeline inspection is achieved together with the location process as the liquid plays the role of couplant, and economic loss is reduced.

To achieve tracking the location pig train and locating the defects, the ULF emitter is designed to emit three kinds of ULF signal: the tracking signal, the locating signal and the helping signal. The tracking signal shows the autonomous pipeline robot's position which is emitted every two minutes and leads maintenance ship to keep up with it. The locating signal is emitted when a defect's position is reached, which goes on for about ten minutes to make the maintenance ship locate the defect's position. When an emergency is encountered, such as power supply failure and electric crawler malfunction, the helping signal is emitted. The

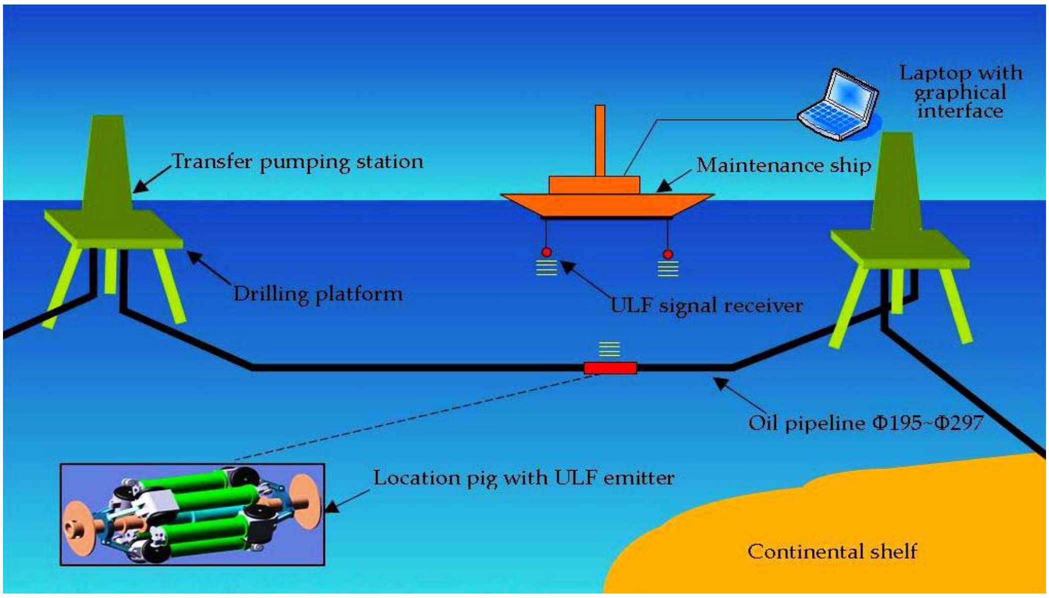

Fig. 6. Overview of on-line location process

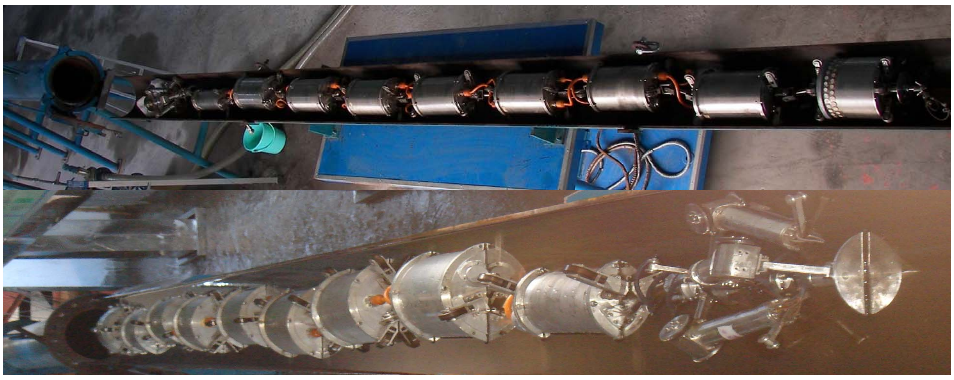

Fig. 7. The upper picture shows the autonomous pipeline robot is ready to launch. The lower picture shows the autonomous pipeline robot moves out of experiment pipeline

communication distance between the ULF emitter and ULF signal receiver is 11m, approximately.

The file which records the pipeline defects' position information is downloaded into the system controller. The system controller will take count of the number of girth weld passed by, which is detected by eddy current sensor. Comparing the girth weld number passed by with defects' position information, system controller judges whether there are defects in the passing through pipe. When there are defects, the autonomous pipeline robot passes through the distance between the defect and the pipe's first girth weld at slow speed, which is measured using the odometer wheels, and then locating signal is emitted. Figure 6 shows an overview of on-line location process.

B. *Experiment*

Since the pipeline maintenance system is used to maintain offshore oil transmission pipelines, a failure could have immense consequences, so before practical application, lots of experiments are made and the testing program is conducted in two-phases: subsection testing and whole testing. The subsection testing includes pressure testing by setting the airtight cabins into pressure vessel full of water and holding at operation pressure for a pre-defined length of time, ULF emitter testing by putting it into a section of pipe and burying the pipe in soil deeply, and electric crawler dragging test, power supply charge and discharge testing and system controller testing. To achieve the whole testing, a experiment pipeline system is set up whose main design specifications are shown in table II.

TABLE II MAIN DESIGN SPECIFICATIONS OF EXPERIMENT PIPELINE SYSTEM

Specification	Data
Material	X56
Full length	98m
Maximum permissible stress	4MPa
Working pressure	2MPa
Flux under working pressure	$31m^3/h$
Pipeline inner diameter	Φ299mm
Bend radius	3D

The experiment pipeline system is also designed to simulate possible pipeline defects in the exact setting location, i.e., corrosion pits and other damage or irregularity. Based on the experiment pipeline system, a situation close to the actual project can be simulated, and any potential difficulties can be dealt with in the workshop.

With the experiment pipeline system, on-line inspection experiments are carried out and water is used as medium. The acquired ultrasonic data are used to extract defect characters and perform automatic defect findings. Experimental results show the defect whose area is more than $10\times10mm^2$ can be detected, measurement error of the pipe's thickness is less than 0.5mm and the defect which affects safe operation can all be identified, while defect's damage degree is overrated sometimes. So the defect's character extraction and defect assessment strategies are effective.

On-line locating defect experiments are made in the experiment pipeline system and figure 7 shows the situation of testing autonomous pipeline robot. Experimental results show the autonomous pipeline robot achieved all locating defect tusks, so the way of locating defects is effective and satisfying.

V. CONCLUSIONS

The set of equipments are developed aiming at maintaining early-built offshore oil pipelines usually unequipped with magnetic markers. The problem of locating defects is perfectly solved with girth welts, playing the role of position mark, instead of the magnetic markers. The inspection pig which has a relatively concise design and low cost meets early-built pipelines' need of periodic inspection to insure safe run. When defects arise, the autonomous pipeline robot is used to carry out the locating defects tusk. From the set of equipments' working principle, obviously, they are competent for newly-built offshore oil pipelines' as well as onshore oil pipelines' maintenance.

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