Development of Ultrasonic Internal Detection Experimental System for Corrosion of Crude Oil Pipeline

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Abstract. Ultrasonic method is one of the important methods for internal corrosion detection of crude oil pipeline, and effective echo signal processing is its key technology. However, if the detection experiment is carried out on the in-service crude oil pipeline, the cost is very high, and it is almost impossible to study the echo signal processing technology. To solve this problem, an ultrasonic internal detection experimental system for crude oil pipeline corrosion is developed by simulating pipeline engineering detection environment, and the characteristics of multi-probe installation, working mode and instrument structure, etc. The system adopts the master-slave structure, 24 ultrasonic probes complete the transmission and reception of ultrasonic signals triggered by the synchronous clock signal, the detection board interacts with the computer through the network, and the offline analysis software automatically analyzes and processes the ultrasonic detection data by using 1.5 dimension spectrum estimation, so as to visually present the pipeline corrosion status and location. Finally, the effectiveness of the system is verified by the ultrasonic detection experiment of internal and external wall corrosion of $\Phi 426 \times 8mm$ steel pipeline.

Keywords: Crude Oil Pipeline, Ultrasonic Internal Detection, Subsystem, 1.5 Dimension Spectrum, Offline Analysis

1. INTRODUCTION

In recent decades, with the rapid development of petroleum industry, the long-distance pipeline used to transport crude oil has also developed rapidly. The medium transported by this pipeline is flammable, explosive, is easy to accumulate with static electricity and volatile. Once the pipeline corrosion occurs, it is very easy to cause crude oil leakage, fire, explosion and other situations, leading to malignant disasters[1,2]. According to the Interim Provisions on safety supervision and management of oil and gas pipelines issued and implemented in April 2000[3]: the new pipelines must be detected within 1 year, and then once every 1 to 3 years depending on the pipeline safety status. As long-distance crude oil pipelines are generally deeply buried underground or under the sea, ultrasonic method is used for periodic internal detection of pipelines and serious defects are repaired in time, which is one of the important technologies to ensure the safe and stable operation of crude oil pipelines[4].

Ultrasonic method is based on the principle of multi-channel ultrasonic automatic flaw detection. The probe array is composed of multiple probes. The ultrasonic wave is emitted from the pipeline to the pipeline wall through the transmission medium coupling. According to the time and size of the echo, the distance between the probe and the inner wall of the pipeline, the residual wall thickness of the pipeline, and the corrosion defects of the pipeline, etc. are detected. In the 1970s, Pipetronix company of Germany took the lead in launching Ultrascan, an ultrasonic detection device in pipe using liquid couplant[5]. In the 1990s, NKK company of Japan successfully developed the ultrasonic pipeline internal detector after five tests in five years from the prototype [6,7]. At present, American GE PII company and German Rosen company have developed EMAT detector[8]. However, foreign pipeline detection companies implement the technology monopoly policy and mostly adopt the method of charging according to the detection mileage, which is expensive. And many detectors are not suitable for China's pipeline conditions. In view of this situation, many domestic universities and scientific research institutions have carried out relevant research in recent ten years. In the late 1990s, in order to reduce the number of detection channels, Shanghai University explored the oil pipeline ultrasonic flaw detection robot with rotating probe scanning and flaw detection[9]. However, due to the special requirements of internal corrosion detection of crude oil pipeline, there are still many technical difficulties in multi-channel, miniaturization, data compression and processing, scanning and imaging and so on.

Due to the limitation of landform, elbows, bends and welding technology are widely used in the laying of long-distance crude oil pipeline, which puts forward high requirements for the trafficability of the detector. At the same time, the operation regime of the actual pipeline is complex and the detection conditions are bad, such as wax deposition on the pipe wall caused by high wax content in crude oil[10], the pressure fluctuation caused

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by the instability of the oil pump and even the sudden interruption operation of a pump station[11,12], stop and go of the detector caused by pipeline blockage somewhere or oil leakage, etc. These unstable factors will have a great impact on the detection results. Therefore, if the detection experiment is carried out on the in-service crude oil pipeline, the cost is very high, and it is almost impossible to study the echo signal processing technology [13].
In order to develop an engineering prototype suitable for corrosion internal detection of long-distance crude oil pipeline, it is necessary to simulate pipeline engineering detection environment, and the characteristics of multi-probe installation, working mode and instrument structure, etc. and establish an ultrasonic internal detection experimental system for crude oil pipeline corrosion.

2. OVERALL SCHEME DESIGN

The ultrasonic internal detection experimental system for crude oil pipeline corrosion shall have the following functions:

(1) Able to simulate the actual detection environment

- Couplant

  Due to the rapid attenuation of ultrasonic in the air, the medium must be used as the coupling agent in the actual pipeline detection, and the oil transported in the pipeline is a good acoustic coupling agent. Therefore, coupling agent is also required for simulation in the laboratory. Water has the advantages of non-toxic, tasteless, no stimulation, no corrosion to ultrasonic probe, good stability and easy access, etc., so it becomes the best choice of coupling agent.

- Liquid path

  A certain distance shall be kept between the ultrasonic probe and the inner wall of the detected pipeline to ensure the detection accuracy and the trafficability of the detector.

- Pipe diameter

  The diameters of crude oil pipeline in service in China mainly include $426mm$, $529mm$ and $720mm$, etc. In this paper, the ultrasonic internal detection experimental system is designed for the detection condition of $\Phi 426 \times (8-16) mm$ long-distance oil pipeline.

(2) Able to simulate the installation and working mode of multi-probe

Due to the requirement of circumferential coverage of pipeline ultrasonic detection, the 24 ultrasonic probes designed in this paper are only a foundation. With the deepening of research, the number of probes will continue to increase, which requires that the installation mode of probes should be easy to adjust. In addition, the method of time-sharing excitation and time-sharing reception of echo signals according to the installation mode of multi-probe is adopted to suppress the mutual interference between echo signals received by multiple probes.

(3) Able to simulate internal detector

Cascade mode of multi section cabin is adopted (a key subsystem is placed in each compartment) to improve the trafficability of the detector in the pipeline.
In short, the system should not only simulate the above detection environment and instrument structure, etc., but also realize the acquisition, amplification and filtering, A/D conversion, online real-time compression and storage of the detection signals, transmission, reading and processing of stored data after the completion of detection tasks, accurate and intuitive display and analysis of pipeline corrosion conditions, traveling driving mechanism and uninterrupted power supply, and there is no missing detection in the coverage area of the probe, so it is very difficult to develop it.
Based on the above design requirements, an ultrasonic internal detection experimental system for crude oil pipeline corrosion is developed, as shown in **Fig. 1**.

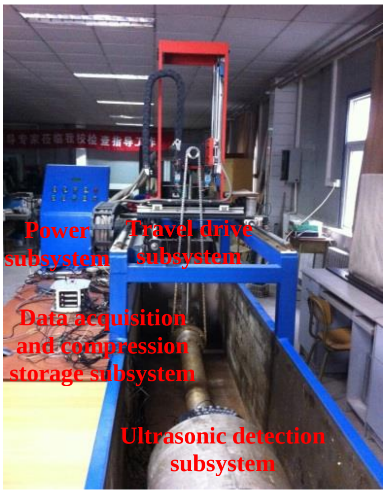

Fig.1 Ultrasonic internal detection experimental system for crude oil pipeline corrosion

The system is an extremely complex system integrating mechanical, electronic, computer and embedded technologies, etc., mainly including ultrasonic detection subsystem, data acquisition and compression storage subsystem, power subsystem, travel drive subsystem, data processing and imaging subsystem, etc., and its working principle is shown in **Fig. 2**.

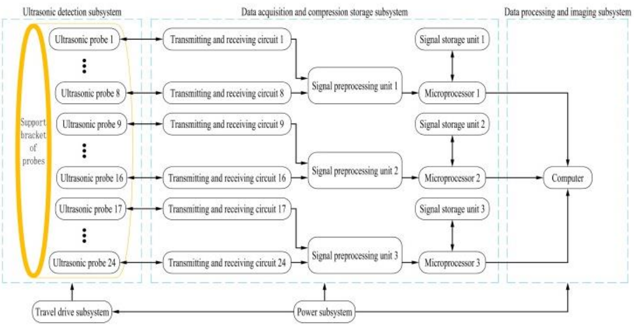

Fig.2 Principle block diagram of ultrasonic internal detection experimental system

24 ultrasonic probes send out ultrasonic signals triggered by synchronous pulse signals, which are received after repeated reflection and transmission on the inner and outer walls of the detected pipeline. The signal is first sent to the preprocessing unit for amplification, filtering, A/D conversion, data compression and cache, etc., and then transmitted to the microprocessor. The microprocessor is responsible for reading the cached ultrasonic detection data, controlling the writing and reading of ultrasonic detection data to the signal storage unit (Flash) and transmitting it to the data processing and imaging subsystem for analysis and processing through the network, so as to display the A-scan waveform, residual thickness of pipe wall and defect distribution.

3. SUBSYSTEM DESIGN

3.1. Ultrasonic Detection Subsystem

The ultrasonic detection subsystem is mainly composed of 24 ultrasonic probes and support bracket of probes.

- Ultrasonic probe

The ultrasonic probe adopts a rigid shell water immersion focusing probe with working frequency of 5MHz and wafer diameter of 10mm.

Because the acoustic beam size of the focusing probe at the focus is very small, the defect recognition ability is improved, but on the contrary, the detection area is very small. At the same time, because the focus is not a point in the strict sense, but has a certain diameter, it should be considered that there should be slight overlap between the focus diameters of each probe in order to ensure no missed inspection. The arrangement sequence of probes of 24 channels is shown in **Fig.3**. This installation method is conducive to the adjustment of the number of probes.

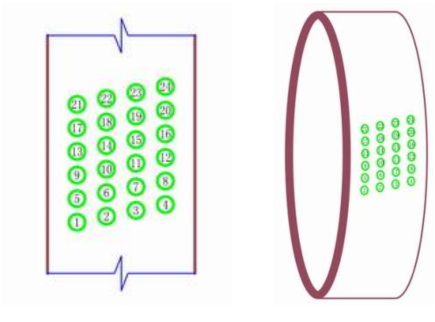

Fig.3 Array diagram of 24 probes

- Support bracket of probes

The support bracket of probes is the antenna of the crude oil pipeline corrosion ultrasonic internal detection experimental system, which is equipped with 24 water immersion focused ultrasonic probes, as shown in **Fig. 4**.

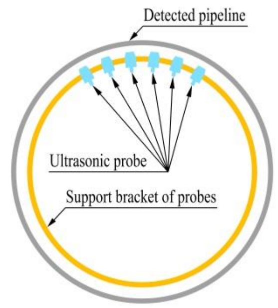

Fig.4 Support bracket of probes

The ultrasonic probe is not in direct contact with the measured pipe wall. After passing through the water layer, the ultrasonic is reflected on the inner and outer surfaces of the measured pipe. The reflected wave received by the probe is processed by the data acquisition and compression storage subsystem to output the A-scan waveform data of each detection point of the detected pipe wall.

During installation, if the directivity of the ultrasonic probe is poor, the focal diameters of adjacent probes may overlap partially or even completely, affecting the detection accuracy. Therefore, each probe should be adjusted perpendicular to the detected pipe wall, so as to ensure that the echo signal accurately reflects the real situation of wall thickness.

3.2. Data Acquisition and Compression Storage Subsystem

The data acquisition and compression storage subsystem is composed of three independent ultrasonic boards. Each board integrates 8 channels and can work independently (only one DC12V power supply and one RJ45 network cable are required to communicate with the computer), as shown in **Fig. 5**.

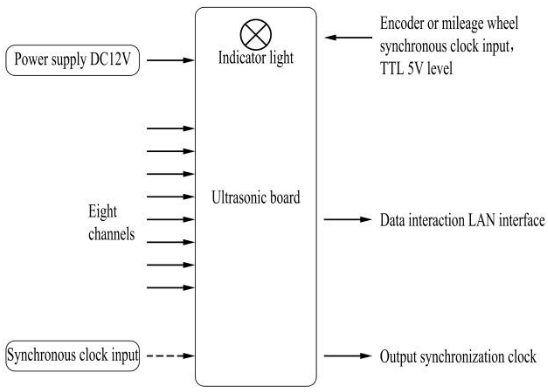

Fig.5 Schematic diagram of single ultrasonic board

The 8-channel data acquisition and compression storage subsystem adopts the board building block combination, and the three independent 8-channel subsystems are connected into a 24 channel acquisition and compression storage subsystem through the network industrial switch, as shown in **Fig.6**.

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Fig.6 Data acquisition and compression storage subsystem

The sampling frequency is 100MHz and the sampling depth is 512b (byte). The data processing and imaging subsystem processes, displays and analyzes the collected ultrasonic signals, and controls the hardware parameters of the acquisition card.

3.3. Power Subsystem

The power subsystem is supplied to the data acquisition and compression storage subsystem in the form of 220V to 12V. When actually detecting the long-distance pipeline, it is necessary to build a high-energy density battery to supply the internal electronic instruments and power devices of the detector.

3.4. Travel Drive Subsystem

Due to the pressure of oil in the process of pipeline transportation, the ultrasonic detection system does not need to use the walking driving subsystem in the actual detection, and can move forward under the push of oil pressure. However, when the sample tube is detected in the laboratory, water is used as the coupling medium, and there is no differential pressure to drive the ultrasonic testing experimental system, so it is necessary to use the mechanical driving mechanism to pull it to move and complete the testing task.

3.5. Data Processing and Imaging Subsystem

After the ultrasonic internal detection system completes the pipeline detection task for a certain distance, it needs to transmit the collected and stored data to the data processing and imaging subsystem for the restoration, processing and analysis of the detection signal to obtain the pipe wall thickness corresponding to each detection point of each channel.

However, if the pipe wall thickness is only displayed by digital way, the shape, size and position of corrosion cannot be seen quickly and intuitively. Therefore, an offline analysis software is developed in this paper. The software includes nine functional modules: opening file module, reading data module, thickness range setting module, data conversion module, graphic drawing module, scanning control module, parameter display module, graphic redrawing module and positioning module. The functional structure is shown in **Fig. 7**.

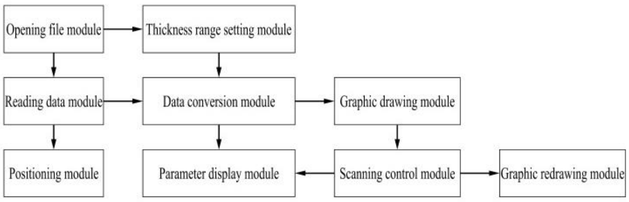

Fig.7 Block design figure of software interface

The software can automatically analyze and process ultrasonic testing data, and clearly present A-scan, B-scan waveform, C-scan image and position information. Through this software, users can comprehensively observe the corrosion status of the pipeline and take timely measures to ensure the safe and efficient operation of the pipeline. The block design of the software interface is shown in **Fig. 8**.

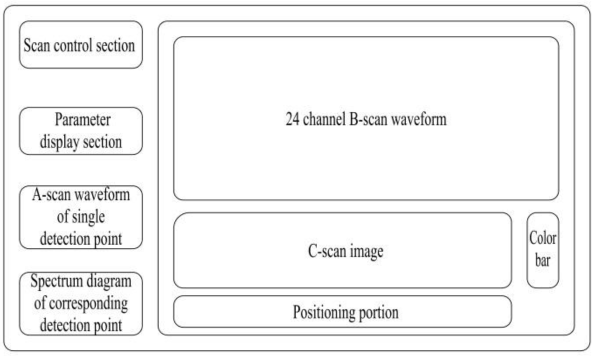

Fig.8 Block design figure of software interface

4. PIPELINE CORROSION DETECTION EXPERIMENT

The core problem of pipeline corrosion detection is to restore and process the compressed ultrasonic A-scan waveform data offline and convert it into B-scan data to form accurate wall thickness information, so as to fully grasp the corrosion status of pipeline. Among them, A-wave data processing is the key technology of internal detection. In this paper, the 1.5 dimension spectrum with nonlinear and non-Gaussian characteristics is used to analyze and process the compression reduced pipeline corrosion echo signal.

4.1. 1.5 Dimension Spectrum[14]

Considering that three-order cumulant and three-order moment of stationary random process $x(n)$ with zero mean are equal, the three-order cumulant is defined as:

$$C_{3x}(\tau_1,\tau_2)=E[x(n)x(n+\tau_1)x(n+\tau_2)] \tag{1}$$

Taking $\tau_1=\tau_2$, we can obtain the main diagonal slice of three-order cumulants:

$$C(\tau)=C_{3x}(\tau,\tau)=E[x(n)x(n+\tau)x(n+\tau)] \tag{2}$$

The 1.5 dimension spectrum of $x(n)$ can be obtained by one dimension Fourier transform of $C(\tau)$, namely:

$$C(\omega)=\sum_{\tau=-\infty}^{\infty}C(\tau)e^{-j2\pi\omega\tau} \tag{3}$$

4.2. Detection Experiment

The ultrasonic internal detection experimental system of crude oil pipeline corrosion developed in this paper is used to scan and detect a section of steel pipeline with artificial corrosion engraved on the inner and outer walls, as shown in **Fig. 9**. The outer diameter of the pipe is 426mm, and the normal wall thickness is 7.9mm. The corrosion I of the pipe inner wall: the width is 26.7mm, the length is one circle along the pipe wall, and the depth is 2mm. The corrosion II of the pipe outer wall: the width is 30mm, the length is one circle along the pipe wall, and the depth is 1.8mm.

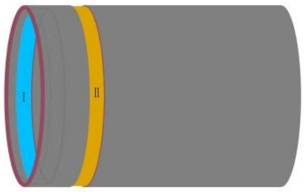

Fig.9 Stereoscopic sketch of steel pipeline for experiment

The working frequency of the ultrasonic probe is 5MHz, the collected ultrasonic A-wave is full detection mode, the detection speed is 7mm/s, the scanning resolution is 0.28mm, the A/D sampling rate is 100MHz, and the A-wave length is 492 points. **Fig.10** shows the A-scan waveform of a detection point of a channel in the offline analysis software.

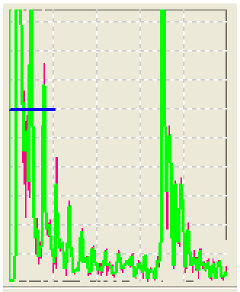

Fig.10 A-scan waveform display interface

The A-wave data of several detection points collected by 24 channels are processed based on the 1.5 dimension spectrum estimation algorithm to obtain the B-scan diagram (shown in **Fig. 11**) and the filtered C-scan diagram (shown in **Fig. 12**).

In **Fig. 11**, the abscissa is sampling numbers (1313 points in total), and the ordinate is the pipe wall thickness automatically calculated by the program. The diagram corresponding to "channel 1 ~ 24" shows the B-scan diagram corresponding to the respective detection areas of 24 ultrasonic probes (displayed in array according to the actual installation mode of probes). From the B-scan diagram, it can be seen intuitively that the residual thickness of the pipe wall at any detection point of any channel, especially between the detection points 400 ~ 600 and 600 ~ 800, the wall thickness is significantly reduced to about 6mm.

The yellow area (outer wall corrosion II) of 24 channels located between the detection points 600 ~ 800 is locally enlarged respectively, and the starting and ending points can be read out in turn, so as to calculate the defect width of each channel here, as shown in **Table. 1**.

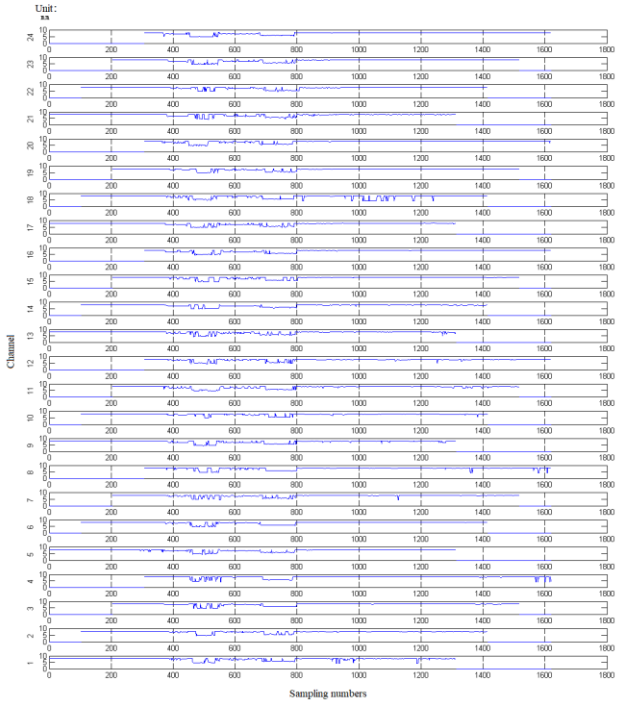

Fig.11 B-scan of steel pipeline for experiment

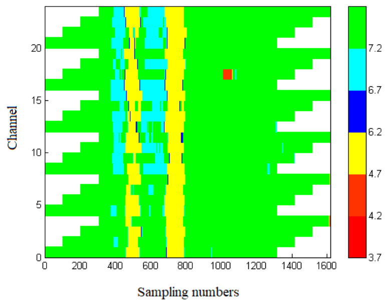

Fig.12 Filtered C-scan of steel pipeline for experiment

Table. 1 Width of outer wall corrosion Ⅱ

Channel number	Starting point of yellow area	Termination point of yellow area	Defect width (mm)
1	692	792	28
2	694	789	26.6
3	691	798	29.96
4	690	785	26.6
5	683	791	30.24
6	683	794	31.08
7	691	785	26.32
8	700	799	27.72
9	694	793	27.72
10	709	779	19.6
11	699	789	25.2
12	700	775	21
13	679	790	31.08
14	685	797	31.36
15	699	790	25.48
16	698	798	28
17	686	783	27.16
18	689	788	27.72
19	697	799	28.56
20	681	784	28.84
21	698	795	27.16
22	696	806	30.8
23	691	789	27.44
24	681	791	30.8

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The average defect width of 24 channels calculated in **Table. 1** is 27.685mm, which is very close to the actual value.

5. CONCLUSION

(1) The installation and working mode of 24-channel probe are designed, the support bracket of probes is made, and the ultrasonic detection subsystem with ultrasonic probes and support bracket of probes as the main body is constructed to realize the vertical directivity of ultrasonic beam emitted by the probe.

(2) The data acquisition and compression storage subsystem is designed to realize the acquisition, signal amplification, filtering, A/D conversion, on-line compression, storage and transmission of 24 channel ultrasonic A-scan waveform data.

(3) Cooperating with power subsystem, travel drive subsystem, data processing and imaging subsystem, an ultrasonic internal detection experimental system for crude oil pipeline corrosion is built, and the hardware support platform for ultrasonic detection data post-processing is realized.

(4) The offline analysis software is developed. The ultrasonic A-wave data are processed based on 1.5 dimension spectrum estimation algorithm. The B-scan waveform and C-scan image can clearly and intuitively reflect the location, size and depth of corrosion, and meet the requirements of defect identification.

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