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## **Design of an oil pipeline nondestructive examination system based on ultrasonic testing and magnetic flux leakage**

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### **Abstract:**

we analyzed the limitations of in-service oil pipeline ultrasonic inspection systems, and devised a scheme of an oil pipeline corrosion inspection system based on several ultrasonic sensors and magnetic flux leakage (MFL) sensors. On this basis, a ultrasonic/MFL pipeline corrosion testing system was successfully proposed in this paper, for which the multi-sensor information integration technology was used for data processing. Corresponding validation test results show that this system has improved the precision and accuracy of oil pipeline damage inspection and is of great pragmatic value in industrial engineering work.

**Keywords:** nondestructive examination, ultrasonic inspection, magnetic flux leakage (MFL) sensors, multi-sensor.

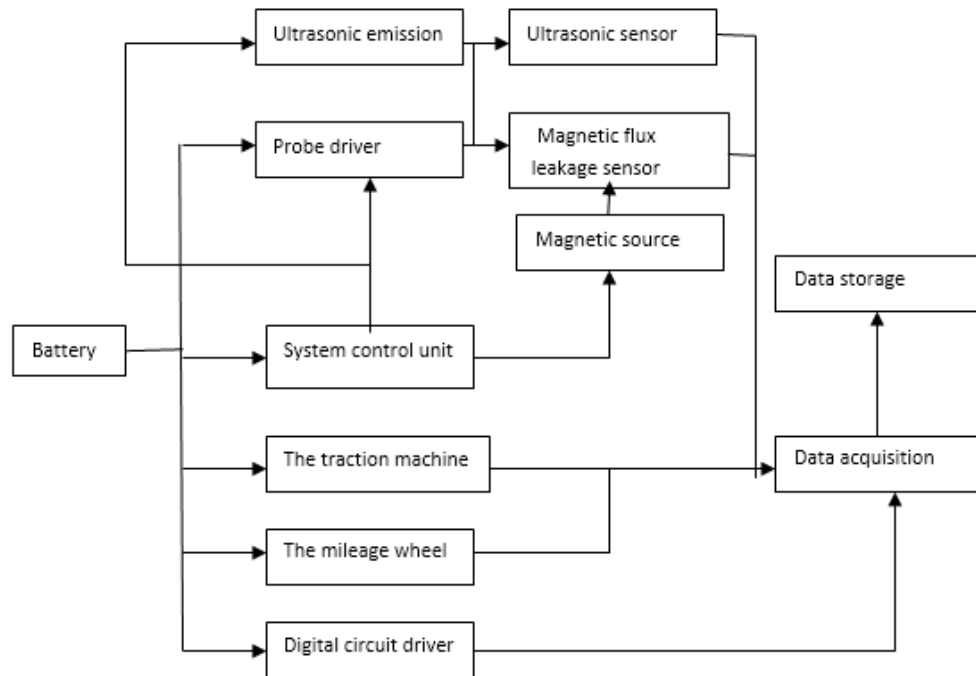
### **1. INTRODUCTION**

Pipelines buried deeply underground or under sea have been applied to the transportation of natural gas and liquid petroleum in many countries. The corrosion or stress crevices on walls of such pipelines occurred during their long-term service have become a major cause to crude oil leakage accidents, and have drawn research attention long before (Wang, 2013) (Li et al., 2010). MFL smart pigs and ultrasonic smart pigs are both effective in inspecting damages in in-service oil pipelines. The former one performs well in fine damage detection such as crevice corrosion and pitting corrosion, but scores worse in wall thickness investigation than the latter one does. On the contrary, ultrasonic smart pigs are good at wall thickness inspection but bad at detecting damages of small size (Li, 2013). Along with the in-depth research conducted on data integration technology and multi-sensor system, multi-sensor based non-destructive testing (NDT) has led the trend. The ultrasonic/MFL based NDT offsets limitations of ultrasonic NDT and MFL NDT (Huet al., 2004) (Lin and Chu, 2015), and instead achieves more accurate inspection results such that providing preciser damage parameters and other information for pipeline maintenance and management.

In addition to the combined use of ultrasonic testing and MDL, the oil pipeline damage inspection system processes data by means of multi-sensor information integration technology (Gu et al., 2000). In this way, with less ultrasonic probes, the system is able to check pipeline damages anywhere for pipeline walls of arbitrary thickness. By the design of several components like ultrasonic/MFL probe parameters, excitation frequencies, and driving probe, we realize ultrasonic/MFL based damage detection with the proposed system in the paper.

### **2. HARDWARE AND PARAMETER DESIGN FOR THE INSPECTION SYSTEM**

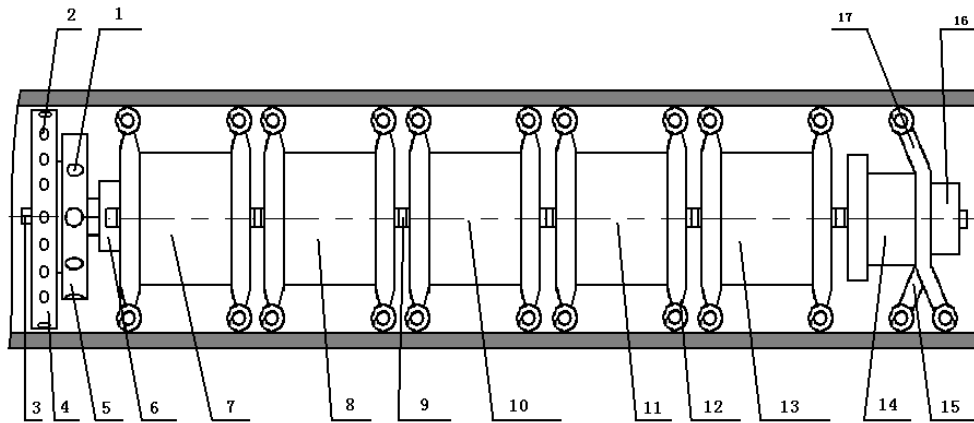
To satisfy the requirements of the inspection system with respect to small size, high reliability, low power consumption and simple programming, our host computer is a combination of data collection/storage system with a PCI embedded IPC. By means of modular design, each module is designed and debugged independently before being assembled as a whole for optimization. In this way, we reduce the complexity of design, control results easily, and minimize design error. Figure 1 shows modules of the non-destructive testing system.



**Figure 1.** The overall design map of the oil pipeline corrosion inspection system.

In this figure, the power supply provides electric power to probe driver, action driver, odometer wheel, digital circuit, and system control & communication unit. With the power supply, the system operates steadily and reliably. The ultrasonic source, magnetic source and their probes constitute a sensor module as the system's final unit which is driven by a probe driver specifically employed to ensure precise probe positioning and operation. The tractor is built in the inspection system and should move forward at the same steady speed in the oil pipeline. The odometer wheel records the axial displacement of the smart pig and realizes data collection and storage. The system control & communication unit, where dialogues between operators and the inspection system are carried on, serves multiple functions through human-computer interaction, including self-inspection of the probe driver, which guarantees precise probe positioning, and adjustment of the tractor's moving speed, which allows the smart pig to stop in time and/or move in opposite directions(Xu et al., 2004).

To work flexibly in the oil pipeline, the inspection system is composed of multi-section cylinders, as shown in Figure 2. The function of each section is also demonstrated in this figure. The first section is a pipe cleaner, whose functions are: (1) rinse the internal wall of the oil pipe to remove dirties; and (2) locate the inspection system from outside of the petroleum pipeline. The second section is a motor chamber which is equipped with such components as DC motor, slip ring, principal axis, bearing and support. There are also two instrument capsules, which contains a variety of modules such as signal transmission/collection module, data storage module, and motor drive control module, and two battery units, in which batteries provide power for the motor and electric instruments.



**Figure 2.** General assembly drawing for oil pipeline NDT.

The ultrasonic probe plate, with evenly distributed ultrasonic probes on its surface, is connected to a MFL probe plate on one side. On and behind the MFL probe plate are MFL probes at fixed interval and a temperature probe, respectively. Considering the causticity of the oil pipeline, integrated Holzer components (UGN3503U) are used in preparation of MFL probes. They should be placed near the to-be-inspected pipeline wall as much as possible to heighten inspection sensitivity. The distance between the sensor and the targeted pipeline wall changes with different diameters of the adapter plate. A total of four probes equipped in the system forms a spiral scanning band during movement(Yuan,2013), and the corresponding formula of helix angle is

$$\beta = \arctan(v / \omega \cdot \pi \cdot D) \quad (1)$$

Where( $\beta$ -helix angle,  $v$ -pig advance speed,  $\omega$  –angular velocity of the probe,  $D$ - the inner diameter of the pipeline)

As the sensitivity and depth of detection is controlled by excitation frequency, characteristic frequencies of the material should be excluded. The characteristic frequency is given by

$$f_g = \frac{50.66}{\mu_{rel} \sigma D_i t} \quad (2)$$

Where  $D_i$ -the inner diameter of the oil pipe,  $t$ -pipeline wall thickness,  $\sigma$ -material conductivity.

For a standard oil pipeline,  $D_i=309\text{mm}$ ,  $t=8\text{mm}$ ,  $\sigma=6.25 \times 10^{-2} \mu\Omega \cdot \text{cm}$ . By substituting these values into equation (2), the characteristic frequency is obtained as 33Hz. In order for the phase difference between damage signal and noise signal to reach up to  $90^\circ$ , we let the frequency ratio( $f/f_g$ )be about 18,i.e.  $f=600\text{Hz}$ (Hess and Lomonosov,2010).

The driving apparatus of this system includes a pair of motors, one of which drives probe plates to rotate and move and the other motivates the tractor. Limited by pipeline space,

a rare earth DC brushless permanent magnet generator is chosen as the actuator with small size, strong motive and high efficiency. To satisfy requirements of rotating speed and power, HTGMAEAI0600C-1 permanent magnet DC motor is used as the probe plate driver, and HTBRR10206716B-001 permanent magnet DC motor as the tractor driver. Meanwhile, a pair of NP1000-22v-1000Ah chargeable Nickel-Lithium batteries provides power for electric structures including probe plate rotating motor, inspection circuits, data-logging circuits and the communication module.

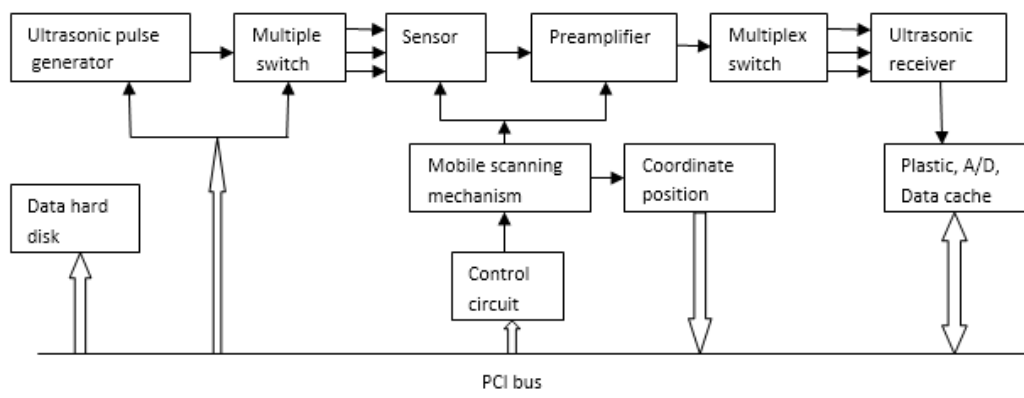
### 3. DESIGN OF THE MULTI-SENSOR SIGNAL COLLECTION SUBSYSTEM

#### 3.1 Design of the ultrasonic sensor signal collection system

The smart pig designed in this paper mainly inspects damages in in-service steep oil pipelines. The propagation speeds of transverse waves and longitudinal waves in steel are 3,230m/s and 5,900m/s, respectively. It merely costs 2.71 $\mu$ s for a ultrasonic wave to pass through a standard 8mm thick petroleum pipeline. Therefore, in order to realize the detection precision of 1%, it is necessary for the system to distinguish 0.0271 $\mu$ s period signals, i.e. The inspection frequency should be over 36.9MHz. Also, the sampling frequency that satisfies Nyquist theorem should be over 75MHz(Tang,2005). PCI bus based high-performance multi-channel ultrasonic transmitting/receiving cards, a self-developed product of Wuhan Zhongke Innovation, Co. Ltd., is employed to this system. The 32-bit PCI local bus structure allows these cards to realize several functions such as ultrasonic wave transmission/reception, 100MHz high-speed signal collection, large-capacity storage, multi-channel auto-control and ultrasonic imaging.

The card is equipped with a displacement sensor control apparatus of two degrees of freedom as well as an integrated driving program, and supports manual hardware control (e.g. sensitivity adjustment, sampling frequency/depth selection) in the form of COM components. It also has four separate transmitting/receiving channels (with about 600V transmitting voltage) and 100MHz high-speed signal collection/treatment chips. Through FPGA, the card completes PCI bridge chip connection, simulation signal control, sample data compression, digital filtering, and distance compensation.

Figure 3 shows the flow diagram of the ultrasonic sensor signal collection system. Under the control of PCI bus, the ultrasonic pulse generator sends pulses to several sensor probes. Echos bounced off the pipeline wall are amplified in the amplifier before being captured by the signal receptor where they are sent to waveform detection A/D adapter. By using PCI bus, the digital signal converted is stored in the data hard disk. In this way, one process of ultrasonic wave collection and storage is completed.



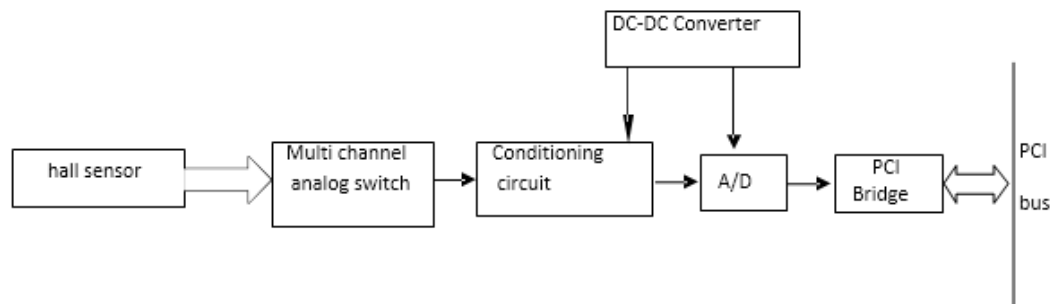
**Figure 3.**Flow diagram of the ultrasonic sensor signal collection system.

Another function of PCI bus is to control and record the rotating speed of the mobile scanning mechanism (probe plates). The corresponding axial position of the odometer wheel is recorded together. These data and the said digital signals are simultaneously stored in the data hard disk during the process of signal transmission/reception, and constitute the complete information required to describe the size and position of an unidentified damage. An active band-pass filter is used to remove interrupt signals during signal collection (Su, 2005).

### 3.2 Design of the MFL sensor signal collection system

The 4 MFL probes surround the inner wall as an array. As each of them is built with 4 Holzer components, there are all together 16-way magnetic signals as input (Jin, 2003). After gated by the 16-way multiplexer composed of 3 MAX4539, the input signals are amplified by the precise differential OP-AMP circuit composed of 3 MAX4108 first and then sent to the A/D conversion circuit as signal output. The A/D adapter used in the paper is MAX1444ADC from MAXIM Corporation. With parameters of 10-bit resolution and 40Msps maximum sampling rate, it totally meets the demand for MFL signal collection and in-time processing. After the system begins to run, the A/D adapter MAX1444 remains at the gating state. CPLD provides it with sampling clock. The front-stage pre-processed input signals are converted into digital signals by A/D adapter and stored in FIFO subsequently. Data reading is done by PCI bus interface chips, the same type as that of the ultrasonic signal detection system.

The MFL signal collection system and the ultrasonic signal collection system share the same PCI bus, such that PCI bus resources are given full play and the design cost is saved. The structure of the MFL signal collection/processing system is divided into several function modules: probe module, signal pre-processing module, modulus conversion module, digital signal treatment module, upper computer interface module, and system power supply module. Figure 4 is the overall structure of the MFL signal collection system.



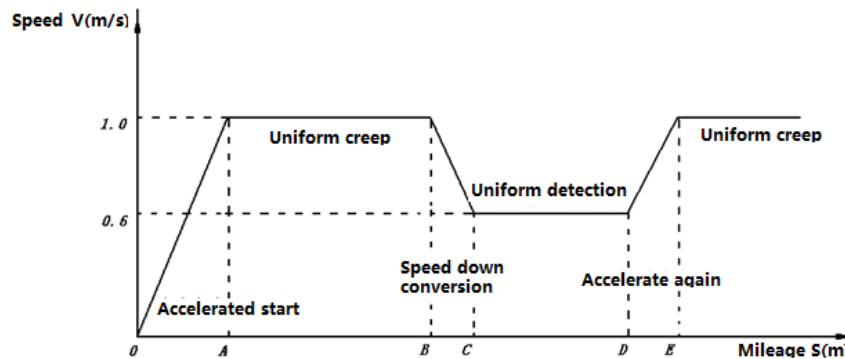
**Figure 4.** The overall structure of the MFL signal collection system.

As shown in Figure 4, the MFL signal detected by Holzer sensors passes in sequence through the multiplexer, the amplification circuit, the A/D adapter where it is converted into standard digital signal, the PCI bridge, and the PCI bus where the converted version is stored in data hard disk. The entire process of data collection is controlled by the control information send from the IPC through PCI bus. The position parameters of MFL detection signals and ultrasonic detection signals can be obtained in the same circuit.

### 3.3 Design of the pig operation state control unit

The smart pig servo system is composed of LM12 circuit, D/A adapter, power amplifier, gain encoder, and DC motor. To alleviate the pressure of data collection/storage as well

as save time, the pig advance velocity and the rotating speeds of ultrasonic/MFL probe plates are free to change with actual situations. When passing along non-damage pipeline wall area, the smart pig moves at the highest velocity. Once capturing suspicious inspection signals, the smart pig automatically decelerate to a certain speed and not switch to the previous speed until the suspicious pipeline section is checked thoroughly. Figure 5 is changes of operating velocity of the smart pig during damage detection.



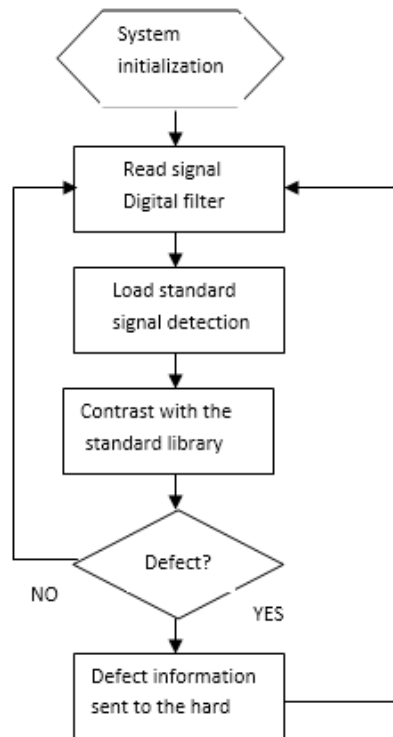
**Figure 5.**Changes of operating velocity of the smart pig during damage detection.

During the process of damage detection, if magnetic flux reaches a fixed amount, the sensor will transfer a pulse signal through FPGA to PCI bus where the pulse will be sent orderly to the D/A adapter of the control system, the power amplifier, and the LM12 circuit which controls the velocity of the motor. According to a default program, the LM12 circuit converts motor speed. Upon receiving the magnetic flux related pulse signal, the control system changes the speed of the motor, one that drives the sensor probe plate to rotate, in a way that guarantees a harmony between it and the updated speed of the smart pig. After the magnetic flux decreases or diminishes, a signal is sent from the clock to the LM12 circuit, which marks the end of the local inspection and that the motor speed can be set back to the original one. Then, the local inspection ends. Data in the gain amplifier are mainly logged down by the data record unit whose task in the control system is to complete feedback to LM12 circuit(Liu et al.,2016).

#### 4.DESIGN OF SYSTEM SOFTWARE

The corrosion inspection system is an intelligent data collection system that allows automatic detection. Its basic functions include: (1) four-probe ultrasonic investigation data collection;(2) acquirement and storage of four-probe MFL investigation data including information of damage location and wall thickness. Figure 6 shows the data collection system for oil pipeline corrosion inspection.

Data obtained from multiple sensors must be combined before an accurate data analysis is conducted. In this paper, the main algorithms applied to data analysis are fuzzy algorithm based linear regression algorithm and filter algorithm as well(Juang and Hsieh,2012)(Wang et al., 2011), with which the ultrasonic detection data as the leading component and the MFL detection data are analyzed within a certain fuzzy interval. Data is combined in multiple layers(Zhang et al.2003). Finally, we determine the size and position of damages as well as whether a size detected falls into the degree to which the area of the size becomes a potential risk or damage. By analyzing the integrated damage data, we identify types of damage (e.g. pitting corrosion, surface corrosion, surface crevices and inner crevices). The output is the severity and geometric feature of the damage, which serves the report of pipeline maintenance/replacement.



**Figure 6.**The flow chart of the data collection system for oil pipeline corrosion inspection.

## 5.ANALYSIS OF SYSTEM PERFORMANCE

According to the result of the corrosion inspection test conducted using this system, the thickness precision and resolution of ultrasonic detection are 0.16mm-0.30mm and 0.2mm, respectively; the minimum precision and maximum depth of MFL inspection are 0.2mm-deep, 0.5mm-wide grooves and 8.3mm, respectively; the precision of the odometer wheel is 0.22mm; the highest advance velocity is 1m/s; the measurement length of the in-service battery is 36km. Table 1 lists the basic parameters of the inspection system.

**Table 1**Basic parameters of the inspection system

| Parameters of the system and its major components | Description                                                                                                       |
|---------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|
| Field of application                              | NDT of liquid petroleum pipelines and natural gas                                                                 |
| types of testable damages                         | Pitting corrosion, surface corrosion, surface crevices and inner crevices                                         |
| Inspection precision                              | Crevice $\geq 0.16\text{mm}$ , groove $\geq 0.5\text{mm} \times 0.2\text{mm}$ , axial position precision 0.22m    |
| A single inspection length in oil pipeline        | 136km                                                                                                             |
| Power                                             | $< 500\text{w}$                                                                                                   |
| Pig advance velocity                              | $\leq 1\text{m/s}$                                                                                                |
| Pipeline radius                                   | $\geq 309\text{mm}$                                                                                               |
| HTGMAEAI0600C-1 motor                             | $\leq 24\text{vDC}$ , rotating speed range 10~1500rpm, $\leq 0.19(\text{Nm})$ , size $\Phi 60 \times 50\text{mm}$ |

|                          |                                                                                                                      |
|--------------------------|----------------------------------------------------------------------------------------------------------------------|
| HTBRR10206716B-00 motor  | $\leq 24\text{VDC}$ , rotating speed range<br>0~1400rpm, $\leq 0.31(\text{Nm})$ , size $\Phi 100 \times 67\text{mm}$ |
| NP1000 battery           | Output voltage 22v, capacity 1000Ah                                                                                  |
| PC IPC                   | A/D, D/A adapter, programmable gain amplifier                                                                        |
| LM12 circuit             | Register of 32-bit velocity and acceleration                                                                         |
| Data collection module   | High-speed data collection card, ADC1600, FPGA logic<br>control panel, 120G hard disk                                |
| ADC1600                  | 16-bit current output                                                                                                |
| DAC0800                  | 8-bit current output                                                                                                 |
| High-speed static memory | ID61LV1024, read-write speed 10ns                                                                                    |

## 6. CONCLUSION

We designed an oil pipeline corrosion testing system based on ultrasonic testing and magnetic flux leakage. This system serves NDT of liquid petroleum pipelines and natural gas pipelines by detecting such damages as pitting corrosion, surface corrosion, surface crevices and inner crevices. With its direct applicability to industrial practices in the field of modernized oil pipeline wireless inspection, this system is of great pragmatic value to transportation and exploration of natural gas and liquid petroleum.

## 7. ACKNOWLEDGMENTS

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