[Research Note]

Automatic Data Acquisition System for Offshore Oil Pipeline
Magnetic Flux Leakage On-line Inspection

Tao Jin*, Peiwen Que, Tianlu Chen, and Qi Zhang

Dept. of Information Measurement Technology and Instruments, Shanghai Jiao Tong University,
1954 Huashan Road, Shanghai 200030, P. R. CHINA

(Received March 16, 2005)

In order to assure the safety of oil pipeline transmission, it is very important to continue routine inspection of offshore pipelines to identify defects or corrosions as early as possible. A high-speed inspection data acquisition system was developed for the magnetic flux leakage (MFL) method, with 12 bit sampling precision and 1.25 M/s sampling frequency. This system consists of a micro-computer, electronic memory, pre-processing circuit, power unit, digital signal processor (DSP), Field Programmable Gate Array (FPGA) and other components. The method adopts hardware and software cooperation to control data acquisition, filtering, encoding, handling, storage and transmission. The main function is MFL signal pre-processing, real-time data acquisition, de-noising and data compression. The basic characteristics of the system, design considerations, data filtering, data compression methods and experiment results are described. Experiments showed the system has a good performance.

Keywords
Pipeline inspection, Magnetic flux leakage, Adaptive filter, Data compression

1. Introduction

The magnetic flux leakage (MFL) method is currently the most common method of pipeline inspection, which can measure and locate defects, corrosion, and cracks in both circumferential and axial directions. The design of offshore oil pipe MFL inspection devices is complicated by the constraints imposed by the miniature size and required capabilities including autonomous operation and adaptability to different environments. To achieve this mode of operation autonomously, we must consider the size, autonomous intelligent operation and driving force. First, the MFL inspection device diameter must be less than the largest pipeline inner diameter (297 mm). Second, very limited space is available for memory, sensors, actuator controllers, and processing units, all of which contribute to autonomous intelligent operation. The design must use all available space to incorporate these conventional solid state components. Third, the MFL inspection device must pass along at least 20 km of pipeline in an inspection process. In contrast to other MFL inspection devices, our device adopts the non-cable driving style. The inspection system which includes the MFL inspection device and ultrasonic pig utilizes oil pressure for power. The ultrasonic pig is only used to locate the defects, and the driving force is water pressure and a driver robot. The driver robot will pass the ultrasonic pig over any defect discovered by the inspection device.

MFL signal on-line data acquisition is a very key process of offshore oil pipeline inspection, which must also meet the requirements of miniature size, autonomous operation, and low power consumption. The quantity of MFL inspection data is enormous and there is much noise in the sample signals, so the data acquisition device must be able to acquire sampling signals, remove noise, and compress data in real time. Here we describe an efficient and high resolution data acquisition system, and present correlative filter algorithms and compression algorithms to remove signal noise and compress inspection data. This system consists of a micro-computer, electronic memory, pre-processing circuit, power unit, DSP, FPGA, and other components. The main functions are MFL signal pre-processing, real-time data acquisition, de-noising and data compression. Data from field testing has proved the good performance of the data acquisition system.

2. Data Acquisition Design of MFL Inspection System

MFL nondestructive testing is an electromagnetic...
technique that can only be used for testing electroconductive material. The method utilizes permanent magnets to magnetize a sample to saturation so the magnetic flux is uniform in regions of no defect, but in regions of reduced thickness, such as corrosion defect or crack, magnetic flux leaks into the air. This leakage flux is correlated with the size and location of the defect, and can be detected by a magneto sensor, allowing the analysis of the pipeline defect parameters from the leakage flux signals.

Figure 1 shows the simplified structure of the MFL inspection device including the pressure tractor, MFL inspection unit, MFL signal processing unit, and power unit. The MFL inspection unit is used to inspect the offshore oil pipeline, and the MFL signal processing unit manages the data. The power unit supplies the system circuits. The driving force is water pressure. Normally, the driving resource of the MFL inspection device is a driver robot. As shown in Fig. 2, the MFL inspection unit includes a transducer array, signal processing circuit and temperature testing circuit. The MFL signal processing unit has a four 32-channel data acquisition module and two IDE hard disks. Control and programmability are provided by a PC104. The power unit supplies all electrical system.

The required detection precision is $10 \times 10 \times 10 \text{ mm}^2$ for a 297 mm offshore oil pipeline. The MFL detector consists of 16 testing units located at equal intervals around the pipeline circumference (Fig. 3). Each unit includes a magnetizing path, 7 sensors and a sensor box. The magnetizing path includes a permanent magnet, magnetizer, and steel brush. Sensors fixed to the PCB are contained in sealed sensor boxes, which are waterproof, oilproof, and withstand high pressure (4 MPa). The permanent magnet is NdFeB, and the magnetizer is ingot iron. A key problem of MFL inspection is to select a suitable sensor to detect the defect flux leakage signal. Table 1 compares several types of magneto-dependent sensors. The magnetic tube has the highest sensitivity, but is non-linear; Mistor has poor temperature features and local linearity; the magnetic test coil has good sensitivity, temperature features and linearity, but can only detect varying magnetic fields. Therefore, the Hall sensor was selected as a relatively stable sensor for MFL inspection. There are two types of Hall sensor at present, the GaAs Hall sensor, and the InSb Hall sensor. Table 2 shows the InSb Hall sensor has higher sensitivity than the GaAs Hall sensor, but the GaAs Hall sensor has better temperature features and linearity. Therefore, the GaAs Hall sensor was selected as the magneto-dependent sensor because of the operation conditions and need for system stability.

Table 1 Comparison of Magneto-dependent Sensors

<table>
<thead>
<tr>
<th>Type</th>
<th>Sensitivity</th>
<th>Anti-interference</th>
<th>Temperature features</th>
<th>Linearity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic tube</td>
<td>highest</td>
<td>not good</td>
<td>about 2%</td>
<td>non-linear</td>
</tr>
<tr>
<td>Magnetic test coil</td>
<td>higher</td>
<td>not good</td>
<td>good</td>
<td>normal</td>
</tr>
<tr>
<td>Mistor</td>
<td>low</td>
<td>normal</td>
<td>not good</td>
<td>local linear</td>
</tr>
<tr>
<td>Hall sensor</td>
<td>higher</td>
<td>normal</td>
<td>&lt; 2%</td>
<td>about 0.1%-2%</td>
</tr>
</tbody>
</table>
The Hall sensor is based on the Hall effect to detect flux density. Figure 4 shows the basic circuit. The Hall electromotive force can be expressed as \( V_h = \frac{IB}{neb} \), where \( V_h \) is the Hall electromotive force, \( I \) is current, \( b \) is thickness of the Hall element, \( n \) and \( e \) is related to the Hall element material, and \( B \) is flux density. Defining \( K_h = (neb)^{-1} \), then

\[
B = \frac{V_hK_h}{I} \tag{1}
\]

From Eq. (1), when \( I \) is a constant, flux density \( B \) is proportional to the Hall electromotive force \( V_h \), so the flux leakage density can be measured accurately by Hall sensors. Figure 5(a) shows the MFL testing circuit. The Hall sensors record the remote field signal. Due to the low signal level expected, a high gain amplifier is required. The inspection signal from each Hall sensor is coupled to the input of an instrument amplifier AD623. To improve the system precision and eliminate the influence of temperature, a temperature measurement circuit is included as in Fig. 5(b). The major circuit is a two-terminal IC temperature transducer AD590, and the output current is proportional to absolute temperature\(^\text{v}1\). The output current from the AD590 is converted to a voltage signal by resistance R5, then is enlarged 50 times in the amplifier in-phase port. The offset voltage \( U_K \) is obtained in the reverse port, then

\[
U_K = (U_T - U_K) \cdot 0.5K_T = 50 \cdot (U_T - U_K) \tag{2}
\]

Figure 6 shows the MFL inspection data acquisition function. The PCI board includes an A/D circuit, 32-channel analog input channels, DSP, FPGA, PCI controller with configuration chip, and three-line SyncBus for synchronized multiboard operation. Input signals include MFL signals, temperature data, location data, etc. The MFL inspection signals are filtered in the DSP module, and then compressed with other data in the FPGA. The central computer controls the data acquisition process through the PCI9054 and stores pipeline inspection data in the storage device.

Good inspection resolution with input voltage is \( \pm 5 \) V requires A/D sampling precision of 12 bit. Single-channel MFL signal sampling frequency is 20 kHz, and the data acquisition board has 32 channels, so the A/D converter minimum sampling frequency should be no less than 640 kHz. The AD1671 A/D converter has

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Type & Sensitivity [mV] & Control current [mA] & Non-linearity [%] & Temperature range [°C] & Temperature coefficient [%/°C] & Input resistance [Ω] \\
\hline
GaAs Hall & 5-50 & 1-5 & 0.1-1.0 & −55-125 & −0.06 & 500 \\
Insb Hall & 20-270 & < 20 & > 1 & −40-125 & −2 & 150-1000 \\
\hline
\end{tabular}
\caption{Comparison of GaAs and Insb Hall Sensors}
\end{table}
12 bit sampling precision and 1.25 M/s sampling frequency. The DSP is the heart of the data acquisition board. The major circuit is a DSP chip TMS320VC5410, flash memory SST39LF400A (4 MB × 16 bit) and RAM CY7C1021BV (62 KB × 16 bit). With the characteristics of enhanced Harvard architecture, hardware multiplier, pipeline organization and efficient special instructions, C54× DSP is especially suitable for an adaptive filter. The MFL inspection signal is transferred through the real time adaptive filter in the DSP to the FPGA. The FPGA generates the address encode for the channel, monitors the remaining memory capacity and informs the PC of the availability of the data transform to the PC RAM disk. Data compression is also completed in the FPGA. We adopted the APEX 20K FPGA. Figure 7 shows the connection diagram of the A/D module and the FPGA. The host PC communicates through PCI interface PLX9054 with the data acquisition system.

3. Experiment Results and Discussion

A schematic diagram of the experimental apparatus is shown in Fig. 8. The apparatus consisted of a small number of components. Pulses were used to start and stop an acquisition, and an AC motor to drive the inspection device in the pipelines. The short aperture delay and low aperture jitter (<50 ps in the external clock/acquisition mode) of the device enabled precise control of acquisition time. The control function in the process environment was implemented by an industrial personal computer. Because these devices are digital systems operating with process-specific software, all analog signals must be converted to digital signals. A/D conversion in the control system was performed by boards or boxes called “analog peripherals” connected to the CPU via the system back-plane bus. Each inspection channel could be programmed independently for one of the standard input ranges (0 to 5 V, 0 to 10 V or 20 V) while operating from a single 5 V supply. The X56 steel pipeline inner diameter was 297 mm.

Figure 9 compares the calculated and tested flux for a 10 × 3 × 1.5 mm rectangular defect. If the noise of the testing signal was removed, the testing flux leakage field value approximated the calculated value very well. If a noise signal was produced by a seamless steel tube, the signal shape and amplitude were similar to the defect signal, so were relevant for system analysis. We adopted the NLMS adaptive filtering algorithm to remove the noise. Figure 10 shows the FIR adaptive filtering system based on the NLMS algorithm. The adaptive filter consisted of an ordinary filter and correlated feedback loop, provided by a FIR filter. If the length of FIR filter unit impulse response \( h(n) \) is \( N \), then the output is given by

\[
y(n) = \sum_{m=0}^{N-1} h(m) \times x(n-m)
\]  

(3)

where \( y(n) \) is a weighted sum, and weight coefficient is \( h(m) \). Figure 10(b) shows the adaptive filter using FIR structures. In the adaptive filter, the weight coefficient can be defined as \( W_i \), then Eq. (3) can be defined as
where \( j \) is time. Therefore, the mean-square error \( E[\varepsilon^2(j)] \) is a quadratic function of weight coefficient.

Pipeline MFL inspection provides a huge quantity of data. This system has 112 Hall sensors, so with an inspection speed of 140 mm/s and inspection data of 2 bytes per position, the total data will be about 30 GB. Therefore, pipeline MFL inspection data must be compressed. The FPGA uses wavelet theory and Huffman coding to compress the MFL data. Huffman coding is a nondestructive compression algorithm. Wavelet transform is a time-frequency transform, which provides both the frequency and time localization in the form of a multiresolution decomposition of the signal. High frequency components are obtained with good time resolution and low frequencies with good frequency resolution.

Figure 11 shows the MFL data compression process based on the wavelet theory and Huffman algorithm. Wavelet transform is a time-frequency transform, which provides both the frequency and time localization in the form of a multiresolution decomposition of the signal. High frequency components are obtained with good time resolution and low frequencies with good frequency resolution.

\[
y(n) = \sum_{j=1}^{N} W_j X(j)
\]

where \( j \) is time. Therefore, the mean-square error \( E[\varepsilon^2(j)] \) is a quadratic function of weight coefficient.

\[
RMSE = \sqrt{\frac{(y_1 - \hat{y}_1)^2 + (y_2 - \hat{y}_2)^2 + \cdots + (y_n - \hat{y}_n)^2}{n}}
\]

\[
CR = \frac{OR}{CF}
\]

Where \( y_n \) and \( \hat{y}_n \) are the signal sampling value and the value after compression and decompression process, respectively, \( OR \) is the original file size, and \( CF \) is the compression file size. The optimum system has high \( CR \) and low \( RMSE \). In our experiments, MFL data \( CR \) ranged from 12 to 17, and \( RMSE \) was as low as 0.01.

4. Conclusion

A MFL inspection data acquisition system was developed, with adaptive filter algorithm and compression algorithm structure based on Huffman coding and wavelet theory. Offshore oil pipeline MFL inspection data can be classified into three types: Health data, non-defect data including valves, branch pipe, annular tubes, etc., and defect data including corrosion, crack, dent, etc. Inspection of offshore oil pipelines has a severe working environment. Removal of noise is a very important problem in data acquisition. The key problem of data compression is to compress defect data
nondestructively. Improvement of the data sampling speed is another important problem for the data acquisition system.

Acknowledgment
This work was supported by China National High-Tech Research and Development ‘863’ Program (Number: 2001AA602021).

References

要　旨
オンライン自動データ取得システムによる海洋送油ラインの磁束漏えい検査

Tao JIN, Peiwen QUE, Tianlu CHEN, Qi ZHANG
Dept. of Information Measurement Technology and Instruments, Shanghai Jiao Tong University,
1954 Huashan Road, Shanghai 200030, P. R. CHINA

油、ガス輸送に利用されている海洋パイプラインにおいて、何らかの原因により生じた機械的損傷あるいは腐食はできる限り速やかに検知する必要がある。本報告においては、磁束漏えい法に基づいたパイプラインの損傷を高速かつ精度良く検知するシステムについて紹介している。その主要なシステムはデータ取得、フィルタリング、データ処理、データ蓄積、および伝送を制御するための適切なハードウェアとソフトウェアからなり、これらの適切な組合せを選択した上で、取得された磁束信号の前処理、リアルタイムのデータ取得、ノイズ除去とデータの圧縮を実現させる機能を有している。ここでは同システムに関わるその特徴、設計における留意点、データフィルタリング、圧縮の意味とともに実験結果につき示した。

J. Jpn. Petrol. Inst., Vol. 48, No. 6, 2005