Long Range Displacement Measurements Systems Using Guided Wave

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Abstract

Magnetostrictive displacement measurement is the main method used to measure the level of a liquid. Many studies have been performed to improve the performance of the system and circuit of the magnetostrictive displacement measurement. However, we found that signal processing is also an important factor in the displacement system. To improve the signal to noise ratio and stability of the magnetostrictive displacement sensor, in this paper we presents coils wound around a waveguide wire as the transmitting and receiving sensor. Both simulation and experiment were performed on the magnetostrictive displacement sensor. We also introduce three methods that could be used to perform signal processing. Results show that the method combination of auto-correlation processing and pike value is the best way to deals with the signal. In addition, the error of the designed magnetostrictive displacement measurement is ± 6 mm.

Keywords: Magnetostrictive, Guided wave, Signal processing, Auto-correlation

1. Introduction

Historically, the basic principle of all magnetostrictive length measurement systems dates back into the past century. The study of electromagnetism revealed physical phenomena, which are partly used by the measurement method presented in this description and implemented in a high-accuracy position sensor for use in industrial applications.

With the rapid development of technology in the field of magnetostrictive displacement measurement, the principles and methods of level measurement have also been developed and updated. Meanwhile, the requirements of magnetostrictive displacement measurement technology have increased the demands of level measurement, such as the measurement of the oil level in high storage tanks and the level measurement of liquid cargo in large cargo ships. The traditional methods cannot meet the current requirements of high accuracy, long-range, and multi-parameter measurement. Therefore, magnetostrictive displacement measurement has been proposed to resolve this problem [1–4]. Compared with traditional sensors, the magnetostrictive liquid level sensor has a long life, high accuracy, multi-parameter measurement, ease of installation and maintenance, and the advantage of easy system automation work. The magnetostrictive displacement sensor has been widely used in large-size, non-contact, high-precision, and harsh environment measurement cases. The working mechanism of the magnetostrictive displacement sensor is based on the Wiedemann effect and Villari effect. Because the sensor and the moving parts are non-contacting, the degree of protection is high and facilitates the longevity of the system. It can also achieve absolute displacement measure-

Received: Aug. 9, 2017
 Revised : Sep. 13, 2017
 Accepted: Sep. 13, 2017

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Figure 1. Structure of magnetostrictive liquid level sensor.

ment and has maintenance-free, self-calibration, and multi-point measurement functions [5–7]. The inductive signal is the most important part of the magnetostrictive displacement sensor. However, because the torsional wave passing through the end of the wire with the damping structure cannot be eliminated completely, it will be reflected several times in the wire. The wire and the wave will be superimposed on each other in the waveguide into the induction coil. In addition, the effects of electromagnetic interference will introduce noise. All of these factors will lead to the instability of induced signals. Most of the current research on the magnetostrictive displacement sensor has mainly focused on mechanism analysis and the circuit design, while the details needed to enhance the quality and stability of the sensor signal have not been considered. In this paper, a time domain and frequency domain analysis of the signal for the induction is carried out to enhance the signal to noise ratio.

2. Working Principle

The magnetostrictive liquid level sensor is composed of a measuring head (including pulse generation, echo reception, signal detection, and processing circuit), the waveguide wire, and magnetic sub-components as shown in Figure 1.

The pulse generator shown in Figure 1 generates the guided

Figure 2. Normal magnetization curve.

wave, which can propagate through the wire. When the guided wave meets the magnetic signal over the liquid level, it will be reflected. The magnetostrictive liquid level sensor utilizes the principles of the buoyancy effect, magnetostrictive effect, electromagnetic effect, and magneto-mechanical effect. The system works by detecting the occurrence of an electrical pulse to the reception from the magnetic sub-return time in order to calculate the interval between pulses position of the liquid level and interface [8, 9]. The excitation pulse is generated from the sensor circuit and the produced end of the waveguide wire at proximal sensor circuit. The instantaneous current propagating along the waveguide wire will produce a circular magnetic field perpendicular to the radial guide wire. The position of the magnet assembly means that an inherent bias magnetic field will be produced. When these two magnetic fields meet, they will be superimposed into a reverse magnetic field. According to Wiedemann effect, reversing the magnetic field will generate an instantaneous torque force [10]. It will then generate a mechanical torsional wave in the waveguide wire, and propagate to the two ends of the waveguide wire. According to the Villari effects, the induction coil to detect the torsional wave signals will generate an induced voltage. Since the speed of current is approximately the same as the speed of light, the propagation time of the speed of current can be ignored. Therefore, by measuring the time interval between the excitation pulse and the induction signal on the waveguide, we can accurately calculate the position of the magnet, to obtain the absolute displacement measurement [11–15].

The propagation characteristics of the guided wave used in the wire are very complicated. The waveguide wire used is Ni-Span-C and its magnetic properties are shown in Figure 2.

A graph of the group velocity of 0–20 MHz for a target wire is shown in Figure 3. The graph was drawn by DISPERSE, which is a wave analysis program developed by the Imperial

Figure 3. Group velocity dispersion curves for the waveguide wire.

College London..

Three types of guided waves can be generated in waveguide wires, $L(n, m)$, $T(n, m)$, and $F(n, m)$, where n and m are integers that represent the circumferential and radial modal parameters, respectively. The L mode and T mode are axial symmetric modes, of which n is equal to 0. The F mode is the non-axisymmetric mode [16–20]. The curve clearly shows that the $T(0, 1)$ mode is non-dispersed for the entire frequency domain, which means that the $T(0, 1)$ mode is a good choice for detecting defects.

We decided to use 64 kHz as the test frequency because it shows excellent detection ability and a narrow bandwidth for generating in a long range without dispersing in the waveguide wire.

3. Experiments

This paper presents a method to improve the accuracy of the magnetostrictive displacement sensor by applying a coil, wound around the waveguide wire, to the transmitting and receiving sensor as shown in Figure 3. An instrument (model MsSR2020) was used to operate the sensor to transmit and receive the signal of the guide wave [21–23]. The direct current was galvanized through the waveguide wire in order to generate a circumferential magnetic field around the waveguide wire. In addition, we set the frequency at 64 kHz, the number of initial signal cycles at 3, the pulse rate at 4, and the current value of the waveguide wire at 1 A.

The signal in the magnetostrictive displacement measure-

Figure 4. Transmitting and receiving sensor of magnetostrictive displacement measurement.

Figure 5. Two methods of receiving a signal: pulse & echo and pitch & catch.

ments system can be received in two ways as shown in Figure 4. The first is the ‘pulse and echo’ method, in which the transmitting and receiving sensors are in the same position. When the signal is generated by the transmitting sensor, it will be propagated through the waveguide wire on both the left and right side. As shown in Figure 4(a), the three routes of the guide wave are propagated in the wire. The first route is the reflection signal from the left end of the wire, the second route is the reflection signal from the right end of the wire, and the third route is the reflection signal from the left end which passes through the receiving sensor and reflects at the right end of the wire. The second is the ‘pulse and catch’ method, in which a transmitting and receiving sensor are used in the two parts of the waveguide wire. While the transmitting sensor generates the guided wave and propagates through the wire, it will be received by the receiving sensor at the other end of the wire.

Using the pulse and echo method to perform the experiment, we observed that the guided wave can be propagated up to 18 mm without dispersing as shown in Figure 6.

Figure 6. Pulse and echo receiving signal (the distances between the transmitting and receiving sensors. (a) 5 mm, (b) 10 mm, and (c) 15 mm.

Figure 7. Propagation of guided waves in the wire.

The length of the waveguide wire is 18 mm. T1 refers to the initial signal from the transmitting sensor, and R1, R2, and R3 are the receiving signals of the receiving sensor by route 1, route 2, and route 3, respectively. From Figure 5 we can see that the amplitude of the guided wave is still strong after being propagated in the long range of the waveguide wire. Therefore, we can use this system to measure the displacement up to and even beyond 18 mm [25–30].

4. Simulation

Before performing the experiment, we conducted the simulation of the $T(0, 1)$ propagation of the guided wave in the waveguide wire using the DISPERSE program. The diameter of the wire is set the same as the real experiment of 0.5 mm.

Figure 7 shows the simulation of different types of generation in the wire of the guided wave mode. The frequency is 64 kHz, the number of cycles is 5, and the amplitude is 10. We can see that the velocities of the $T(0, 1)$, $L(0, 1)$, and $F(1, 1)$

Figure 8. Simulation result of $T(0, 1)$ mode in different positions. (a) 5 mm, (b) 10 mm, and (c) 15 mm.

modes differ. The figure clearly shows that the $F(1, 1)$ mode guided wave can be dispersed during the propagation, which makes it difficult to exactly measure the receiving time of the signal, while it decreases the accuracy of the measurement. We therefore chose the $T(0, 1)$ mode to perform the simulation and experiment with the different positions of the sensors.

Figure 8 shows the receiving signal of simulation when the receiving sensor is in a different position using the $T(0, 1)$ mode. The figure clearly shows that the times at which the signal is received differ according to the position of the sensor; we can thus calculate the position of the sensor by capturing the receiving time of the signal processing

The typical method used to perform the signal processing of the magnetostrictive displacement measurement is to calculate the time difference of the pike value between the initial signal and the receiving signal. In this paper, we use the wavelet and the combination of auto-correlation processing and pike value to perform the signal processing and to obtain better accuracy of the system.

Auto-correlation is a mathematical representation of the degree of similarity between a given time series and a lagged version of itself over successive time intervals.

Figure 9 is the peak value of the receiving signal from the experiment, while Figure 10 shows the calculation velocity of the $T(0, 1)$ mode in a different position.

We also form a wavelet with the receiving signal and obtain the results shown in Figures 11 and 12.

We finally used the combination of auto-correlation processing and pike value with the receiving signal and obtained the results shown in Figures 13 and 14.

By comparing the results of these three methods, it can be seen that the calculation velocity of the $T(0, 1)$ mode most closely agrees with the simulation result. In addition, the error

Figure 9. Peak value of receiving signal in different positions. (a) 0.5 mm, (b) 1 mm, (c) 1.5 mm, (d) 2 mm, (e) 2.5 mm, (f) 3 mm, (g) 3.5 mm, (h) 4 mm, and (i) 4.5 mm.

of the measurement is 6 mm, which is an improvement on that for the magnetostrictive displacement product in Korea at present.

Figure 10. Calculation velocity of the T (0, 1) in different positions using peak value.

Figure 11. Wavelet of receiving signal in different positions. (a) 0.5 mm, (b) 1 mm, (c) 1.5 mm, (d) 2 mm, (e) 2.5 mm, (f) 3 mm, (g) 3.5 mm, (h) 4 mm, and (i) 4.5 mm.

Figure 12. Calculation velocity of the T (0, 1) in different positions using peak the wavelet.

5. Conclusion

This paper presents a transmitting and receiving sensor of the magnetostrictive displacement measurement consisting of a wire wound around a coil, and introduces three methods to process the receiving signal. We derived the following conclusions:

1) We use MsSR2020 and two coils (as the sending and receiving sensors) to constitute the displacement sensor, which was able to detect a long range up to 18 mm or even more.

2) In order to improve the accuracy, we attempted to superimpose the different methods to perform the signal processing. In addition, we discovered that the auto-correlation method with

Figure 13. Wavelet of receiving signal in different position. (a) 0.5 mm, (b) 1 mm, (c) 1.5 mm, (d) 2 mm, (e) 2.5 mm, (f) 3 mm, (g) 3.5 mm, (h) 4 mm, and (i) 4.5 mm.

the peak value catch added is the best method.

3) The error of the displacement sensor in this study is about ± 6 mm.

Acknowledgements

This study was supported by the Business for Cooperative R&D between Industry, Academy, and Research Institute fund of the

Figure 14. Calculation velocity of the T (0, 1) in different positions using peak the wavelet.

Korea Small and Medium Business Administration in 2015 (No. C0221107), and the Ministry of Trade, Industry and Energy (MTIE) through the Regional Innovation Centre program (No. B0010843).

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