Development of RFECT System for In-Line Inspection Robot Considering Extendibility of Receiving Sensors based on Parallel Lock-in Amplifier

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This paper proposes a new and effective approach to design a remote-field eddy current testing (RFECT) system equipped with a large number of sensors in order to provide full circumferential coverage of pipelines larger than 6 inches. By developing a parallel digital lock-in amplifier (LIA), the extendibility of receiving sensors can be achieved, and therefore, the modification of RFECT systems, which should be accompanied by sufficiently securing the receiving sensors whose number increases with the pipeline size, can be minimized. Using the design method for an RFECT system based on a parallel digital LIA, a new non-destructive testing (NDT) platform that can be applied to RFECT systems of various sizes without modifying the system architecture is developed. It is then applied to an RFECT system that can be mated with an in-line inspection (ILI) robot and has 36 receiving sensors to inspect unpiggable gas pipelines. The performance of the RFECT system is verified with respect to the sensitivity and the accuracy of defect characterization though the pull-rig test having a number of artificial defects.

1. Introduction

In-line inspection (ILI) technology has been a cornerstone for sustaining the integrity of pipelines in global infrastructures and has utilized several kinds of useful non-destructive testing (NDT) systems, such as magnetic flux leakage (MFL), ultrasonic testing (UT), and electromagnetic acoustic transducer (EMAT). As the conventional ILI tools referred to as “smart pigs” are propelled by the differential pressure between the front and rear of the tool body, the pressure of pipelines should be kept above a specified pressure. In the case of natural gas pipelines, the operating pressure should be maintained above 20 kgf/cm², and a special launching and receiving trap must be installed in order to stably deploy the conventional ILI tools to the pipeline. Pipelines that satisfy the above-mentioned conditions and for which the deployment of conventional smart pigs is possible are called “piggable” pipelines. Conversely, pipelines that cannot be inspected by smart pigs due to internal obstacles that exist in the itinerary of smart pigs in the pipeline and/or insufficient pressure are deemed “unpiggable” pipelines. Distribution mains mostly classified as unpiggable pipelines are buried in highly congested areas worldwide and are about three times longer than trunk pipelines, piggable pipelines that connect metropolitan cities. Thus, the need to inspect the unpiggable pipelines moving along in the interior of pipeline has arisen in the gas industry and necessitated ILI robots able to self-propel and negotiate obstacles.

In order to develop an ILI robot for unpiggable pipelines, the selection of NDT technology suitable for the operating environment in unpiggable pipelines and the general limitations of ILI robots are very important. As the untethered type of ILI robot usually designed for long-range inspection is battery operated, NDT technology able to supply high performance in terms of sensitivity, detectability, and accuracy of defect sizing as well as minimize power consumption is preferred. Among the several common NDT technologies prevalent in the conventional ILI tools for piggable pipelines that are applicable to ILI robots, remote-field eddy current testing (RFECT) technology is considered the optimal NDT technology. The advantages of RFECT
technology are as follows. Unlike MFL and EMAT, RFECT systems usually do not cause a big drag force, because they do not need to maintain strong contact with the pipe wall or use strong permanent magnets and the couplants between the sensor and pipe wall in UT are not necessary. In addition, RFECT systems differ from ECT systems, in that they can detect defects on not only the external side but also the internal side of the very thick pipe walls by virtue of double-through-wall inspection. Moreover, RFECT systems are very useful for ILI robots that have to minimize the module size to pass through obstacles (e.g., short-radius and mitered bends, tees, back-to-back bends, vertical sections, valves), because all of the components of RFECT systems can be made small (i.e., up to half the size of the pipe diameter).

In RFECT phenomenon, the eddy current induced by the electromagnetic wave from the exciter coil propagates from the internal surface to the outside of the pipe wall. It then induces a secondary magnetic field that has the same frequency as (but a slightly shifted phase) the original exciting wave due to the time delay caused in the through-wall propagation process. Then, the secondary electromagnetic wave travels along the pipeline and again induces an eddy current on the external surface at the remote-field zone in which the direct magnetic field from the exciter is almost attenuated. The remote-field zone usually starts from a distance two diameters away from the exciter coil. The propagation of the eddy current from the outside to the inside of the pipeline happens in the remote-field zone, and signals coupled with anomalies on both sides of the pipeline can be measured by magnetic field sensors. The thickness changes in the pipe wall are reflected in both the amplitude of the signal and the phase difference, but the phase difference is more dominant and useful to characterize the defects, since the phase difference can maintain a certain value according to the wall thickness in spite of the sensor lift-off or unstable dynamic behavior of tools. Therefore, the precise measurement of the phase difference of the signal in the remote-field zone is a key factor that determines the overall performance of the RFECT system. A lock-in amplifier (LIA) is a well-known signal measurement instrument able to measure the phase difference and amplitude of an AC signal even if the amplitude of the raw signal is at the microvolt level and almost covered by noise.

This technique involves conducting strong low-pass filtering after multiplying the measured and amplified signal and reference wave whose frequency is the same as the measured signal and whose phase can be controlled according to the operation environment. A general LIA generates two kinds of outputs. One is called the in-phase signal, which is the result of multiplying the measured signal and the reference wave, which can be expressed as a cosine function. The other is called the quadrature signal, which is the complementary signal of the in-phase signal that is obtained by shifting the phase of the reference wave 90 degrees before inputting the reference wave to the mixer in the LIA.

It is difficult to implement RFECT technology inspection tools for large-diameter pipelines, because many receiving sensors are necessary to ensure the full circumferential coverage of the pipeline, and consequently, the same number of LIAs with receiving sensors is required to implement an RFECT system for large-diameter pipelines.

A review of the preceding RFECT technology suggests that even state-of-the-art RFECT systems with multi-channel sensors still have problems with the simultaneous measurement of the phase difference between the signals coming from all of the receiving sensors and the reference wave and the extendibility of receiving sensors. Thus, RFECT systems need to be modified for the inspection of large-diameter pipelines. Therefore, this paper proposes a new and effective approach to design an RFECT system equipped with a large number of sensors in order to ensure full circumferential coverage of pipelines larger than 6 inches. By adopting the parallel LIA, the extendibility of receiving sensors can be achieved, and therefore, the modification of RFECT systems, which is accompanied by sufficiently securing the receiving sensors whose number increases with the pipeline size, can be minimized. Using the design method for an RFECT system based on parallel digital LIA, a new NDT platform that can be applied to RFECT systems of various sizes without modifying the system architecture is developed and applied to an RFECT system that can be mated with an ILI robot and has 36 receiving sensors to inspect unpiggable gas pipelines. The performance of the RFECT system is verified with respect to the sensitivity and the accuracy of defect characterization through the pull-rig test having a number of artificial defects.

2. RFECT System Architecture Based on Parallel Digital LIA

The type of defects to be found and pipeline features, such as diameter and pipe wall thickness, must be considered as key parameters in designing the RFECT system. RFECT systems having array-type sensor coils with high resolution are applied to the inspection of large-diameter pipes to enhance the detectability of localized defects and ensure full circumferential coverage of the pipes. At the same time, absolute and differential types of sensor coils have been applied to the inspection of small-diameter pipelines, such as heat exchangers in power plants. Due to the problem of full circumferential coverage of pipelines, it can be said that the only option is to use array-type sensor coils in the design of RFECT systems for large-diameter pipelines.

The basic purpose of RFECT systems is to precisely measure time delay, which varies according to pipe wall thickness and is usually expressed as the phase difference at a specified exciting frequency between the original exciting source and sensor signals. Thus, simultaneity in the signal acquisition and process is crucial in multi-channel RFECT systems.

An LIA is a necessity when measuring the phase difference between each signal from multi-channel sensors and one exciting source that has a specified frequency and phase. An LIA is a kind of signal measurement instrument that is used to measure very weak signals that may be hidden in background noise of much higher amplitude than the actual signal that needs to be measured. An LIA is a frequency- and phase-sensitive AC voltmeter that allows the detection of a weak signal at a specific frequency and phase provided by a reference source.

By conducting strong low-pass filtering after multiplying the reference wave of the exciting source and sensor signal that is amplified as specified gain, it is possible to remove the frequency term and obtain a value interlocked with the phase difference. This signal process causes time delay, and it becomes a main restriction of the inspection speed in multi-channel-type RFECT systems. Therefore, to