Technical Progress on

INNOVATIVE ELECTROMAGNETIC SENSORS FOR PIPELINE CRAWLERS

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Notice

Abstract

Internal inspection of pipelines is an important tool for ensuring safe and reliable delivery of fossil energy products. Current inspection systems that are propelled through the pipeline by the product flow cannot be used to inspect all pipelines because of the various physical barriers they encounter. Recent development efforts include a new generation of powered inspection platforms that crawl slowly inside a pipeline and are able to maneuver past the physical barriers that can limit inspection. At Battelle, innovative electromagnetic sensors are being designed and tested for these new pipeline crawlers. The various sensor types can be used to assess a wide range of pipeline anomalies including corrosion, mechanical damage, and cracks.

Battelle has completed the second year of work on a projected three-year development effort. In the first year, two innovative electromagnetic inspection technologies were designed and tested. Both were based on moving high-strength permanent magnets to generate inspection energy. One system involved translating permanent magnets towards the pipe. A pulse of electric current would be induced in the pipe to oppose the magnetization according to Lenz's Law. The decay of this pulse would indicate the presence of defects in the pipe wall. This inspection method is similar to pulsed eddy current inspection methods, with the fundamental difference being the manner in which the current is generated. Details of this development effort were reported in the first semiannual report on this project. The second inspection methodology is based on rotating permanent magnets. The rotating exciter unit produces strong eddy currents in the pipe wall. At distances of a pipe diameter or more from the rotating exciter, the currents flow circumferentially. These circumferential currents are deflected by pipeline defects such as corrosion and axially aligned cracks. Simple sensors are used to detect the change in current densities in the pipe wall. The second semiannual report on this project reported on experimental and modeling results. The results showed that the rotating system was more adaptable to pipeline inspection and therefore only this system will be carried into the second year of the sensor development. In the third reporting period, the rotating system inspection was further developed. Since this is a new inspection modality without published fundamentals to build upon, basic analytical and experimental investigations were performed. A closed form equation for designing rotating exciters and positioning sensors was derived from fundamental principles. Also signal processing methods were investigated for detection and assessment of pipeline anomalies. A lock in amplifier approach was chosen as the method for detecting the signals. Finally, mechanical implementations for passing tight restrictions such as plug valves were investigated. This inspection concept is new and unique; a United States patent application has been submitted.

In this fourth reporting period, the rotating system inspection was further developed. A multi-channel real-time data recorder system was implemented and fundamental experiments were conducted to provide data to aid in the design of the rotating magnetizer system. An unexpected but beneficial result was achieved when examining the separation between the rotating magnet and the pipe wall; separations of over an inch could be tolerated. Essentially no change in signal from corrosion anomalies could be detected for separations up to 1.35 inches. The results presented in this report will be used to achieve the next deliverable, designs of components of the rotating inspection system that will function with inspection crawlers in a pipeline environment.

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Executive Summary

The basic requirements for sensor systems designed for installation on pipeline crawlers include small physical size and weight as well as low electrical power consumption. Magnetic flux leakage, the most common technology used to inspect pipelines, is difficult to implement on autonomous crawler systems because the systems are inherently large and heavy. The objective of this project is to develop electromagnetic sensors for mounting on a crawling inspection platform that moves slowly through the pipeline interior. These sensors will be used to assess a wide range of pipeline conditions including corrosion (pitting, patches, and general), mechanical damage, cracking, and seam weld defects. The sensors must be light weight and low drag to minimize propulsion requirements of the crawler platform. In addition, the sensors will require minimal power for excitation of interrogating energy and sensor current for anomaly detection.

In a three year development, the focus of work in the first year has been on prototype development. The first semiannual report covered the development of a translating permanent magnet induced pulsed eddy current system. The second semiannual report covered the development of the rotating permanent magnet exciter to induce eddy currents for the inspection of pipelines. Since the results showed that the rotating system was more adaptable to pipeline inspection, only this system was be carried into the second year of the sensor development. The third semiannual report documented basic analytical and experimental investigations of the rotating magnet system. A closed form equation for designing rotating exciters and positioning sensors was derived from fundamental principles. A lock in amplifier approach was chosen as the method for detecting the signals. Finally, mechanical implementations for passing tight restrictions such as plug valves were investigated. This inspection concept is new and unique; a United States patent application has been submitted.

In this fourth reporting period, the rotating inspection system was further developed. A multi-channel real-time data recorder was implemented and fundamental experiments were conducted to provide data to improve in the design of the rotating magnetizer system. An unexpected but beneficial result was achieved when examining the separation between the rotating magnets and the pipe wall, separations of over an inch could be tolerated. Essentially no change in signal from corrosion anomalies could be detected for separations up to 1.35 inches. The next objective is designing critical components of the rotating inspection system to function with inspection crawlers in a pipeline environment.

Background

By rotating permanent magnets inside a pipe along its longitudinal axis, one produces an alternating electrical current in the wall of the pipe. Figure 1, a cutaway drawing showing the rotating permanent magnet exciter, illustrates a concept that has the potential to induce strong eddy currents in the pipe wall. In contrast to traditional eddy current systems, which use a coil that is driven by a sinusoidal current, this approach uses alternating N and S poles rotating around a shaft. The dashed lines in Figure 1 illustrate the current flow as the magnetizer rotates in the pipe. The current flows in an elliptical path around the magnets. When the magnetizer is vertical, strong currents flow axially along the sides of the pipe and circumferentially at the top and the bottom. When the magnetizer is horizontal, strong currents flow circumferentially at the sides of the pipe and axially at the top and the bottom. Modeling shows that a two-pole magnetizer produces strong current densities at distances well away from the magnetizer.[1] Although the current is complex at the magnet poles (where it is strongest), at a pipe diameter or more away from the magnetizer it is uniform and sinusoidal.

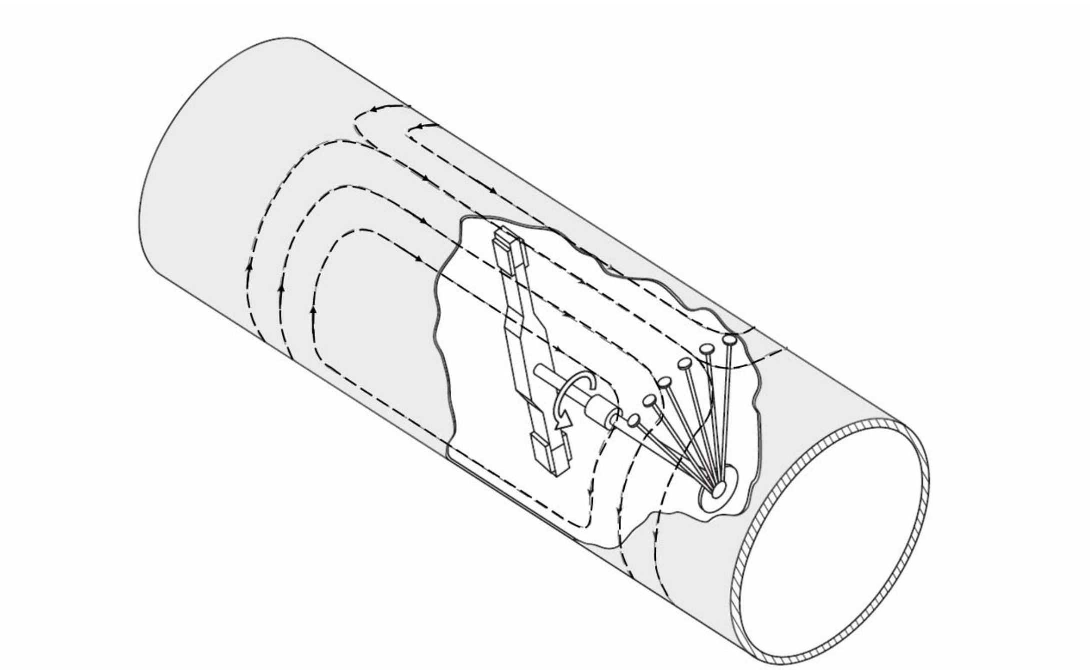

Figure 1. Illustration of the rotating permanent magnet exciter and sensor location

Figure 2 shows a prototype for a pipeline with a diameter of 300 mm (12 inches) and a wall thickness of 9 mm (0.375 inch). Two pairs of NdFeB magnets are mounted on a steel core machined from 1018 steel. The magnets are 50.8 mm (2 inches) long, 25.4 mm (1 inch) wide, and 12.7 mm (0.5 inch) thick; the magnet strength is 305 kJ/m^3 (38 MegaGauss-Oersted). While the magnets have a strong attraction to the steel core, aluminum guide rails keep the magnets precisely on the core. The air gap between the magnet and the pipe wall is 12.7 mm (0.5 inch). Wheeled support plates keep the magnet centered in the pipe. A variable speed direct current motor is used to rotate the magnetizing assembly.

[1] The finite element results presented in this paper were obtained using a three-dimensional rotational analysis problem solver that could calculate the current generated by a permanent magnet passing a conductor (Opera-3d® from Vector Fields, Ltd., Aurora, Illinois).

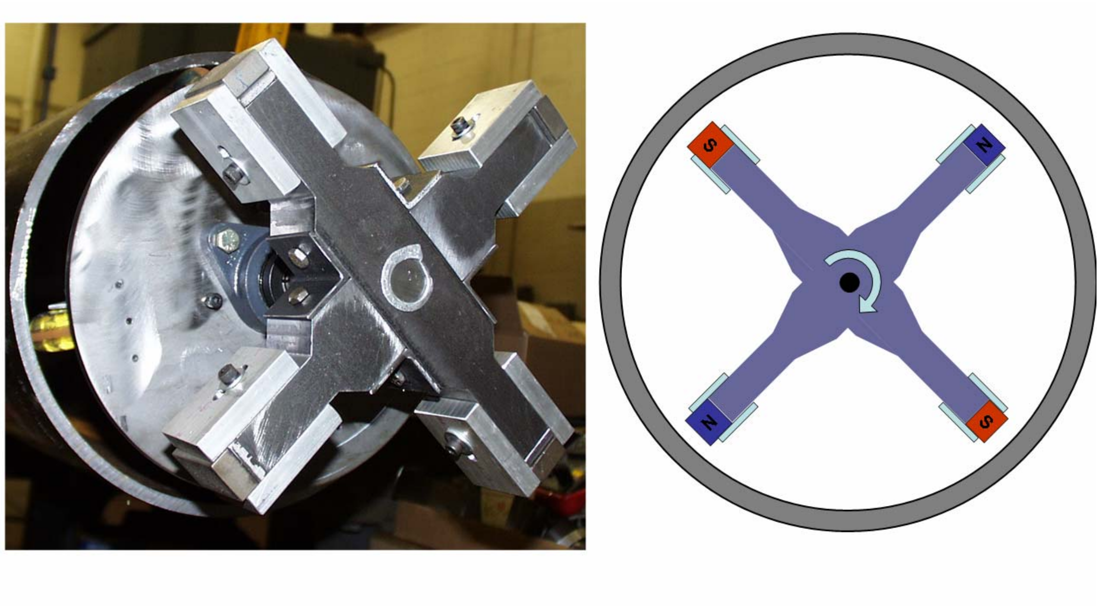

Figure 2. Two-pole rotating permanent magnet exciter for 305 mm (12-inch) diameter pipe

The magnetic field at the sensor has two parts. One part is the direct magnetic field from the strong permanent magnets. The second field is due to the current flowing in the pipe. Figure 3 illustrates the differences in signals when the sensor is near and far away from a pair of rotating magnets in a pipe with a diameter of 305 mm (12 inches). When the sensor is near the rotating magnets, the direct field from the magnet is dominant and produces a saddle-shaped alternating signal. When the sensor is positioned farther away from the magnets, the magnetic field caused by the currents flowing in the pipe dominates. The magnetic field at the sensor due to direct field is negligible at distances greater than one pipe diameter (1D) and the measured signal is nearly sinusoidal. Spectral analysis reveals higher-order odd harmonics are more than an order of magnitude smaller than the fundamental. The magnetic field strength at a pipe diameter away from the rotating magnets is on the order of 0.1 mT (1 gauss), depending on rotational frequency and magnet to pipe separation.

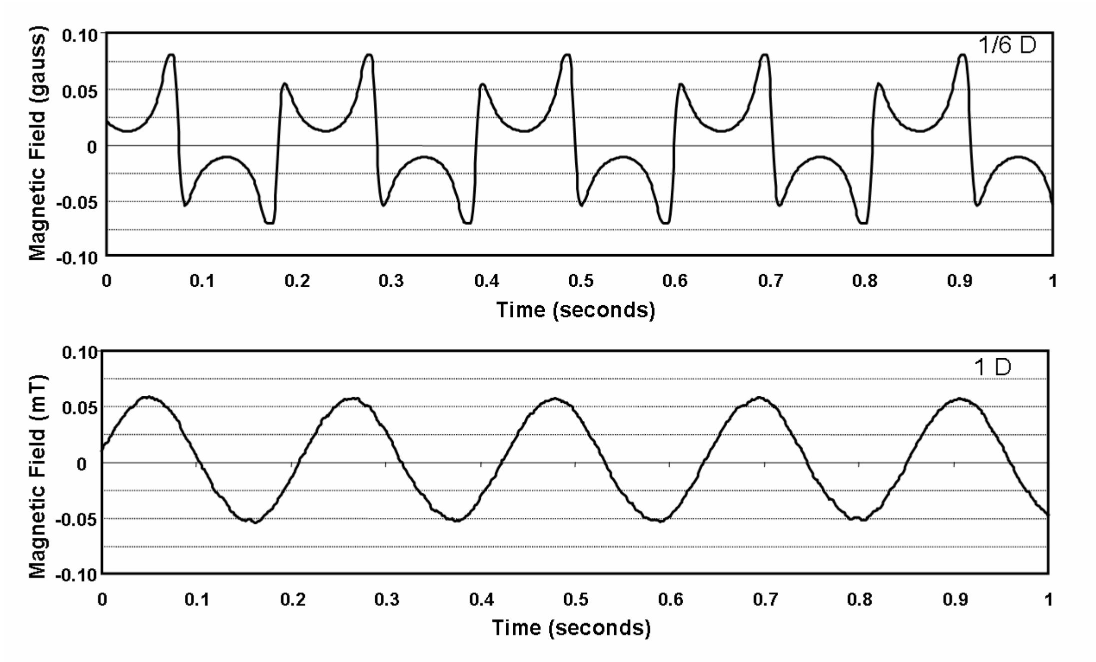

Figure 3. Magnetic field at the ID surface of the pipe near the exciter (top) and one pipe diameter away (bottom)

Experiments

In this reporting period, a multi-channel real-time data recorder system was implemented and fundamental experiments were conducted to provide data to aid in the design of the rotating magnetizer. Multiple sensors distributed around the circumference of the pipe are needed to measure signals from anomalies in an efficient manner. In this reporting period, a multi-channel real-time data recorder system was implemented. The goal of the recorder is to demonstrate that multiple channel sensor data could be simultaneously recorded and processed in a practical and efficient manner. For the rotating magnetizer system, two sensor orientations, axial and radial, are used to detect and quantify the pipeline anomalies. A system was designed to simultaneously record and process 12 sensor pairs, or 24 Hall Effect sensors. The block diagram of the system is shown in Figure 4. The heart of the recorder is the National Instruments PXI-4472, an eight-channel dynamic signal acquisition module for making high-accuracy frequency-domain measurements. The eight NI PXI-4472 input channels simultaneously digitize input signals over a bandwidth from 0.5 Hz to 45 kHz. We have synchronized three PXI-4472 modules to provide 24 channel input using the PXI chassis and a star trigger bus. The PXI chassis communicates with a desktop computer using a fiber optic link. The desktop computer is used to analyze the signals using a lock-in amplifier approach, as described in the previous semiannual report. LabVIEW software modules for lock-in amplifier measurements were used in the development of a custom data acquisition and display program. A typical output of the data recording package is shown in Figure 5. In real time display mode, the data scrolls along the monitor as the inspection tool traverses inside the pipe. The upper and lower graphs show the axial and radial sensors respectively using a staircase plotting routine. In this figure, the signal from anomaly MC1 of the September benchmarking defect set can be seen in middle channels of each sensor type.

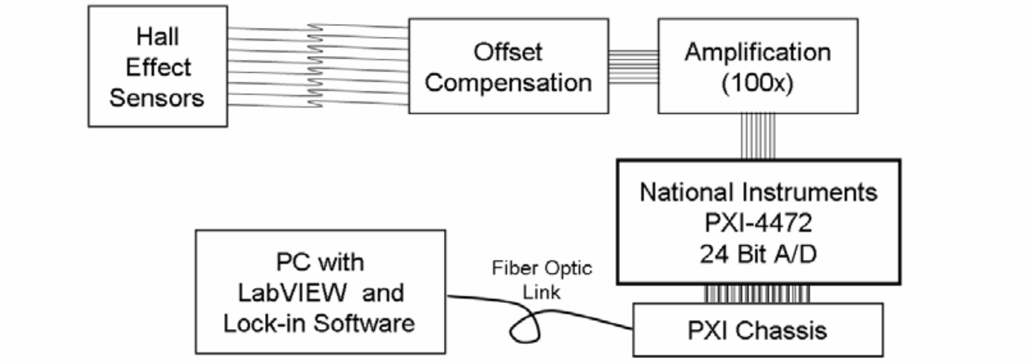

Figure 4. The block diagram of the data acquisition system

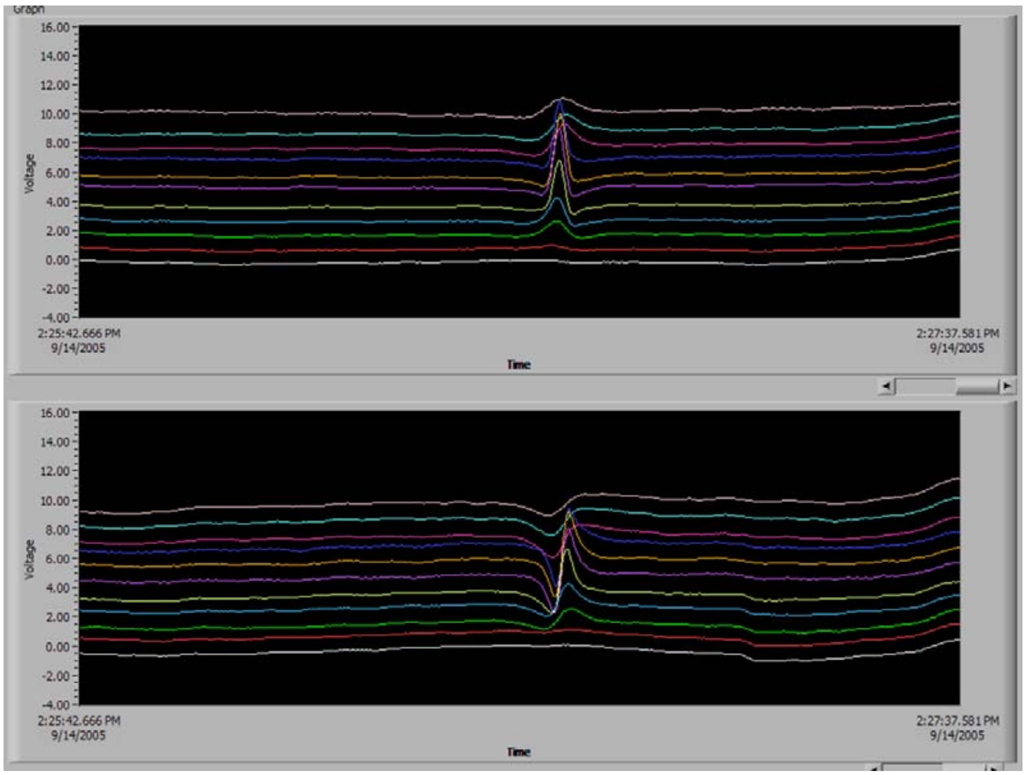

Figure 5. Display of custom LabVIEW data acquisition and display program

Results

Corrosion Anomaly Detection

The rotating permanent magnet inspection system and new data acquisition system was used to collect signals from the anomalies used in the benchmark tests conducted in September of 2004[2].

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[2] "Pipeline Inspection Technologies Demonstration Report," Department of Energy, National Energy Technology Laboratory, Strategic Center for Natural Gas and Oil, 2004.

Two inspection variables, rotational speed and magnetic to pipe separation were examined for the entire length of the pipe. The results are shown in Figures 6, 7 and 8 with the following parameters:

- Figure 6: Frequency is 4 hertz, magnetic to pipe separation is 0.75 inches
- Figure 7: Frequency is 8 hertz, magnetic to pipe separation is 0.75 inches
- Figure 8: Frequency is 4 hertz, magnetic to pipe separation is 0.45 inches

In each figure, the upper graph displays the axial signal component and the lower graph shows the radial component for eleven sensors. The spacing between each sensor was nominally 0.5 inches. The defects include:

- a 25% circumferential groove
- two partial penetration welds
- MC1 – an 80 % deep, 3 inch wide, 1.2 inch long metal loss
- MC2 – an 35 % deep, 1.2 inch wide, 3 inch long metal loss near a weld
- MC5 – an 60 % deep, 2 inch wide, 1.2 inch long metal loss
- MC7 – two 48 % deep, 1.1 inch wide, 1.1 inch long metal loss
- MC9 – an 80 % deep, 1.5 inch wide, 2 inch long metal loss near end of the extent of travel of the inspection tool as configured.

The figures show that the 25% groove and the 60% and 80% pits were clearly detectable at all rotational speeds and magnetic to pipe separations. The shallower pit anomalies, while not as distinct in this representation, are detectable signal processing methods that combine the axial and radial signals. However at the faster rotation speeds, the signal levels are lower. Varying the magnet to pipe separation showed no significant change in signal amplitude, while background noise levels increased when the magnet was closer to the pipe. Since a decrease in signal amplitude was expected for increasing liftoffs, further experiments were performed to quantify this phenomenon. If this phenomenon holds true, then larger pipe to magnet separations will be possible simplifying the implementation of this inspection method.

To quantify the magnet to pipe separation, the distance from the pipe to the magnet was varied from 0.45 to 1.35 inches. Metal loss anomaly MC1 was examined at 6 magnet to pipe separations at 4 and 8 Hz with the results shown in Figure 9 and 10. The anomaly signals appear very similar for all liftoffs; Figure 11 quantifies this result by plotting the peak to peak signal amplitude for the separation distances examined. By increasing distances to even greater distances, it is expected that the signal amplitude will decrease, however significant modification to the current magnetizer design would be required to conduct this experiment. Separations of over an inch provides sufficient flexibility in the design of the inspection system and further quantification will be performed only if required by new design requirements.

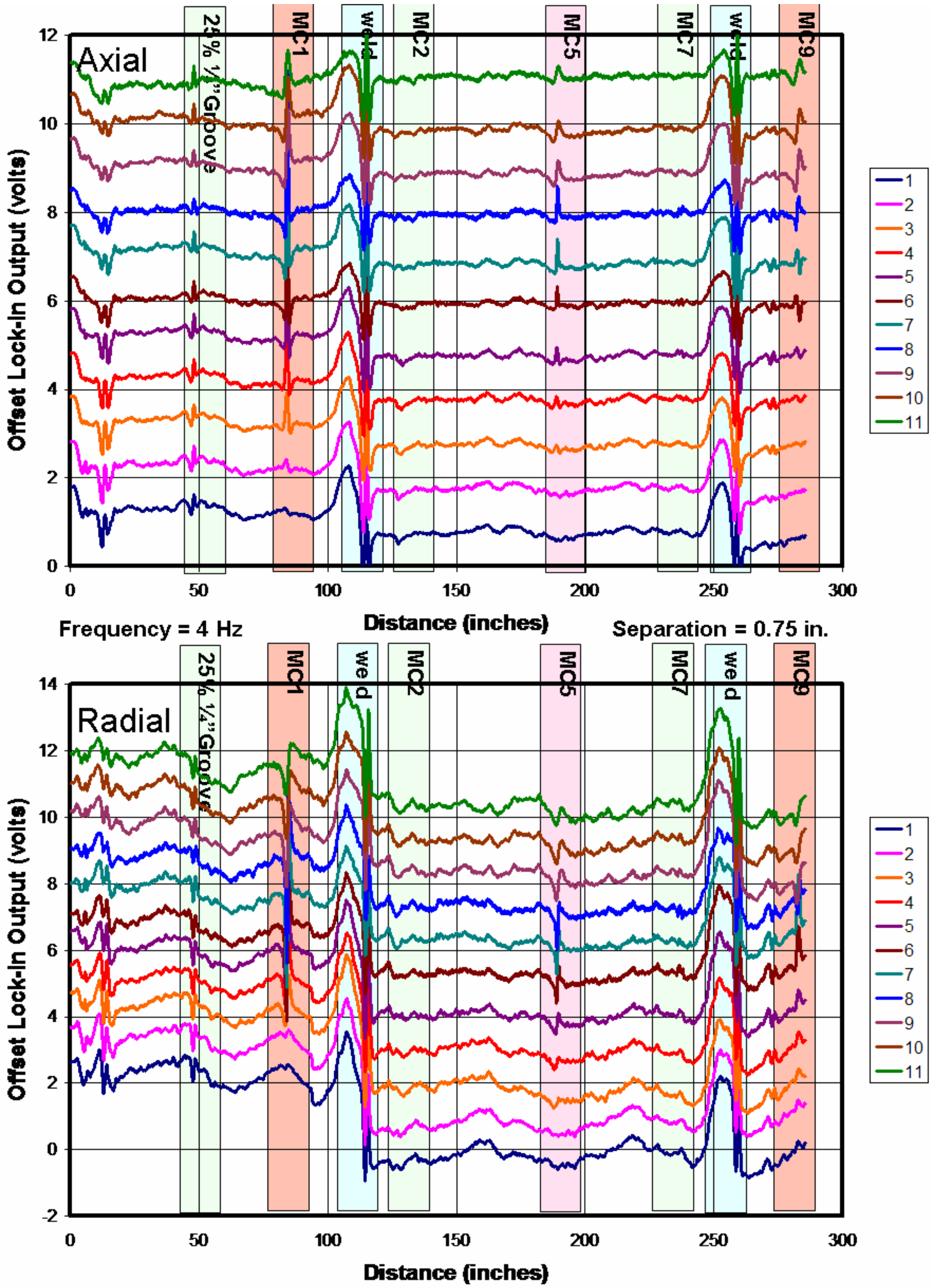

Figure 6. Axial and radial signals from benchmark pipe at a frequency of 4 hertz and a magnet to pipe separation is 0.75 inches

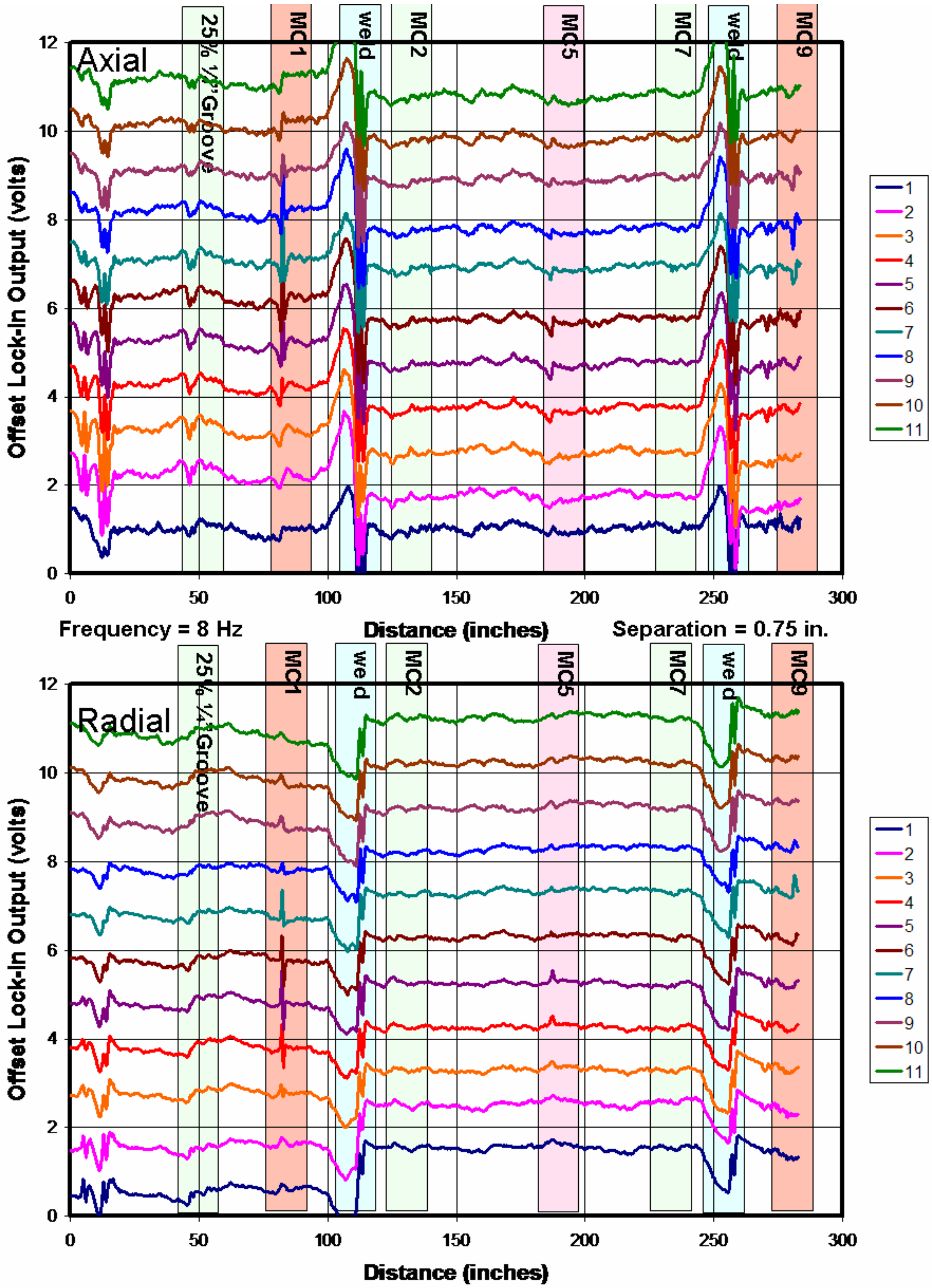

Figure 7. Axial and radial signals from benchmark pipe at a frequency of 8 hertz and a magnet to pipe separation is 0.75 inches

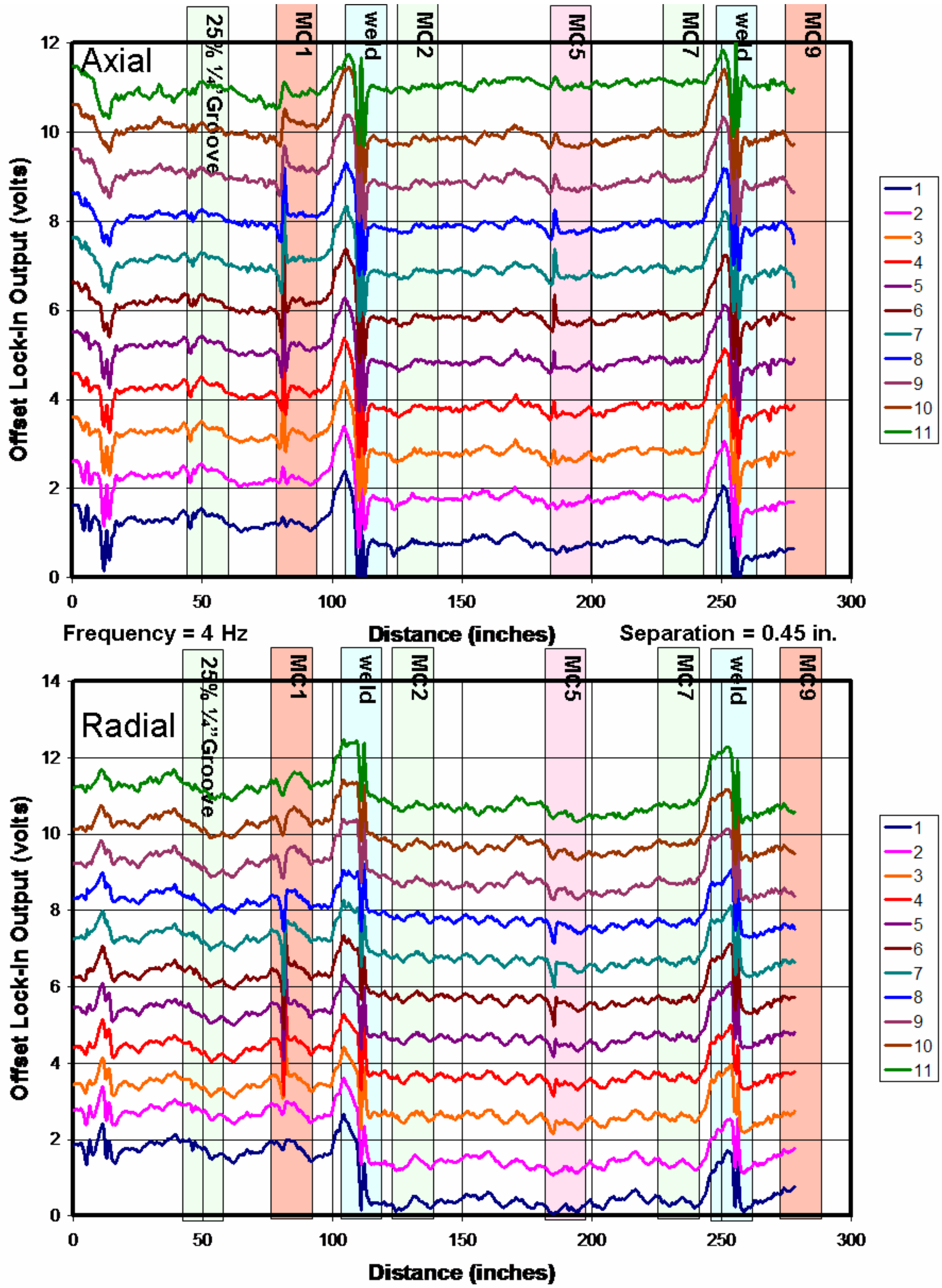

Figure 8. Axial and radial signals from benchmark pipe at a frequency of 4 hertz and a magnet to pipe separation is 0.45 inches

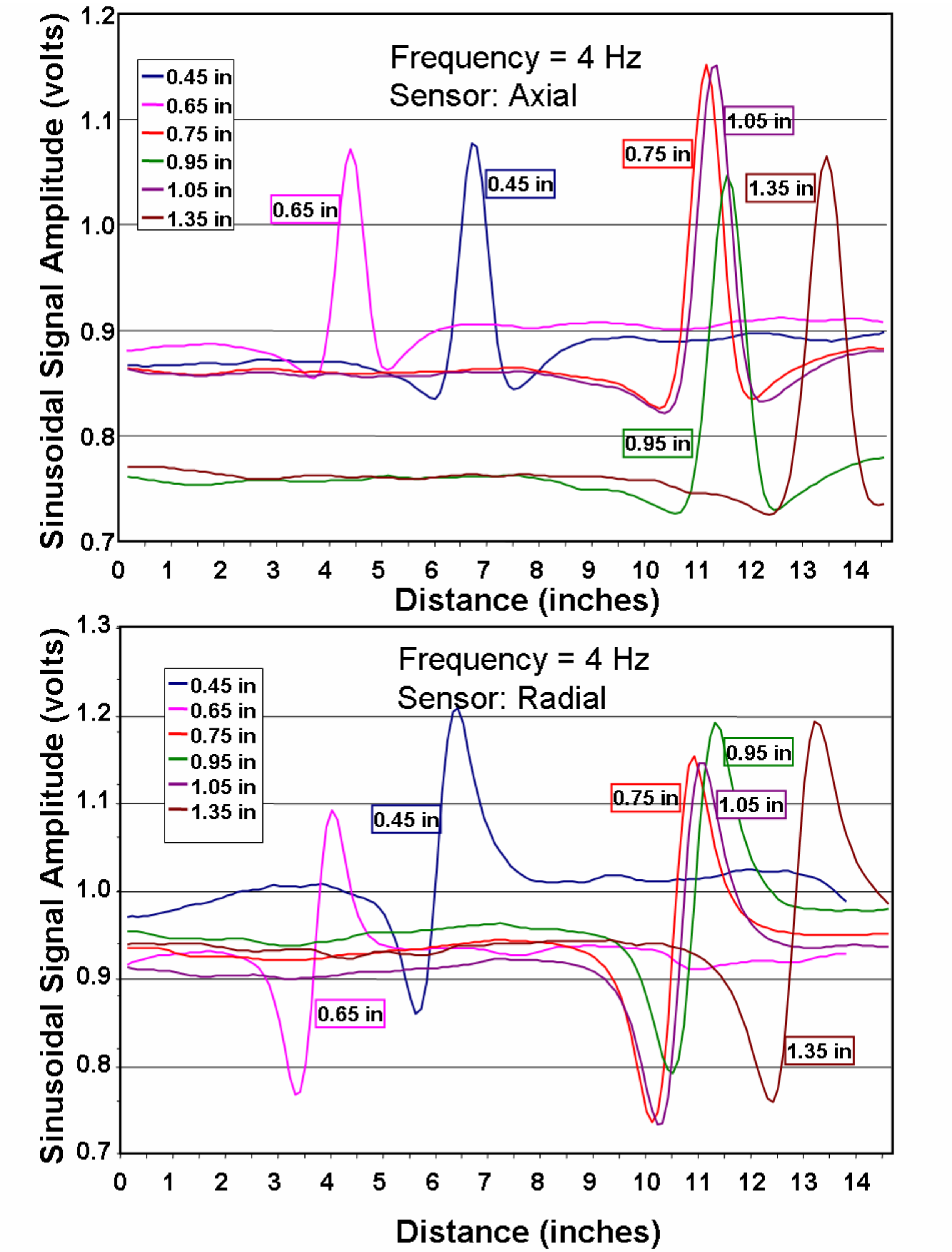

Figure 9. Axial and radial signals from benchmark anomaly MC1 a frequency of 4 hertz and a magnet to pipe separation ranging from 0.45 inches to 1.35 inches

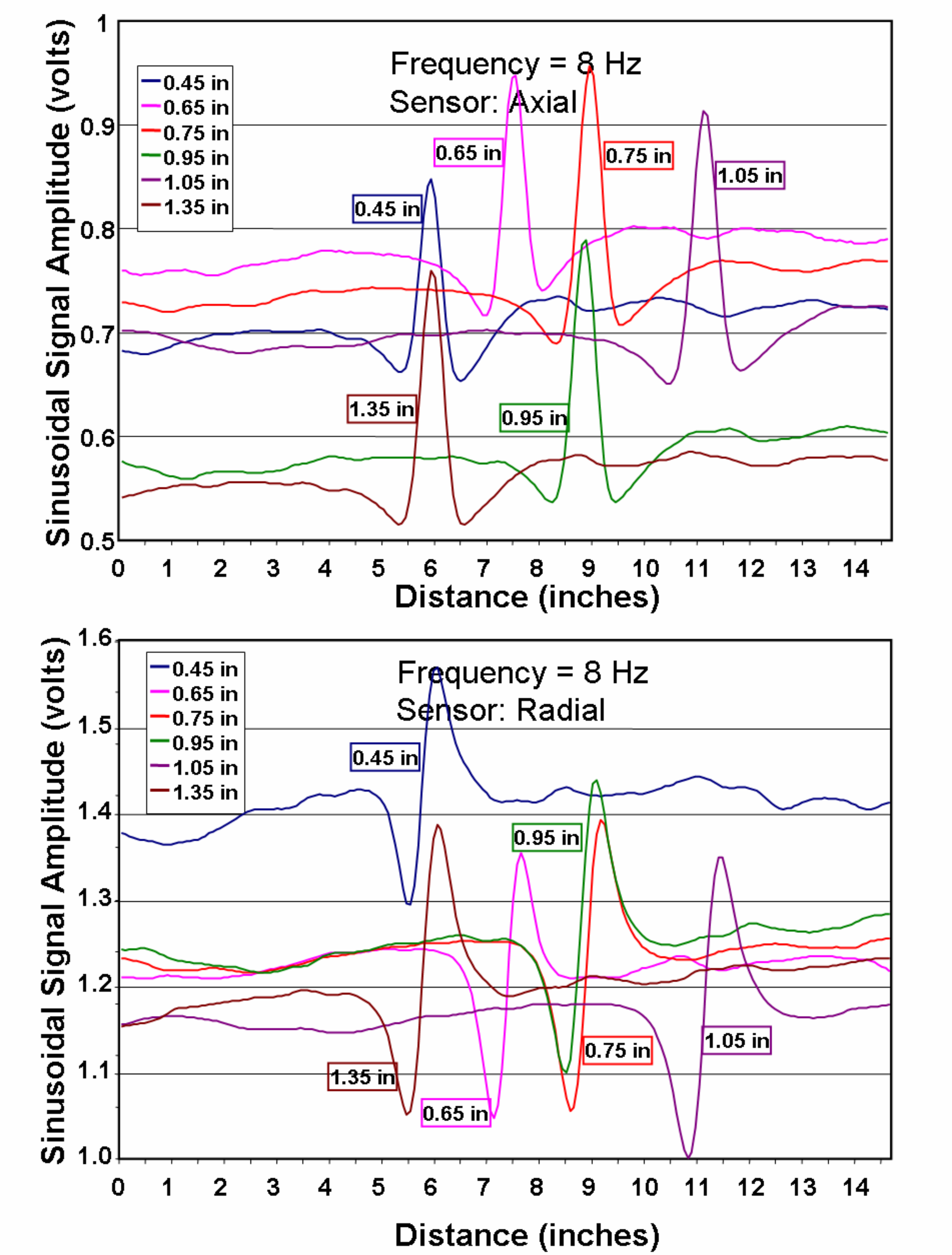

Figure 10. Axial and radial signals from benchmark anomaly MC1 a frequency of 8 hertz and a magnet to pipe separation ranging from 0.45 inches to 1.35 inches

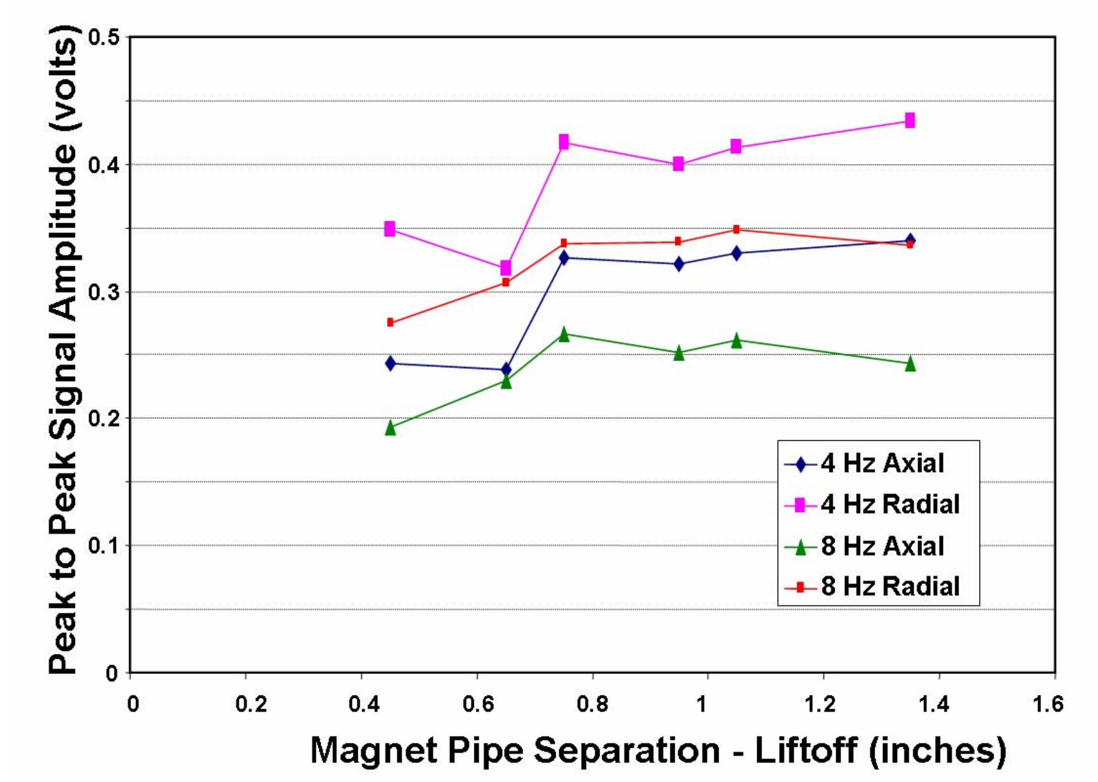

Figure 11. Peak to peak signal amplitude for the separation distances examined

Sensor Position

The magnetic field in the pipe has two parts, each with distinct properties and effects. One part is the direct magnetic field from the strong permanent magnets. The second field is due to the current flowing in the pipe. Near the rotating magnets, the direct field from the magnet is dominant and produces a saddle-shaped alternating signal. Farther away from the magnets, the magnetic field caused by the currents flowing in the pipe dominates. For 12 inch diameter pipe, experiments showed that positioning the sensor approximately 12 inches (300 mm) or more from the magnetizer could be used to attained signal dominated by the current in the pipe. This distance may not be practical for some configurations, particularly smaller diameter pipe. To further reduce the direct field, a potential of a magnetic shield between the magnet and the sensors was investigated. The concept is illustrated in Figure 12. The shield is made of a ferromagnetic material such as steel and is slotted to reduce the generation of circumferential eddy currents being generated in the shield which would reduce the currents in the pipe. Unfortunately, this configuration did not prove useful as illustrated by the signals shown in Figure 13. The signal for the configuration with the shield is smaller in amplitude and more distorted.

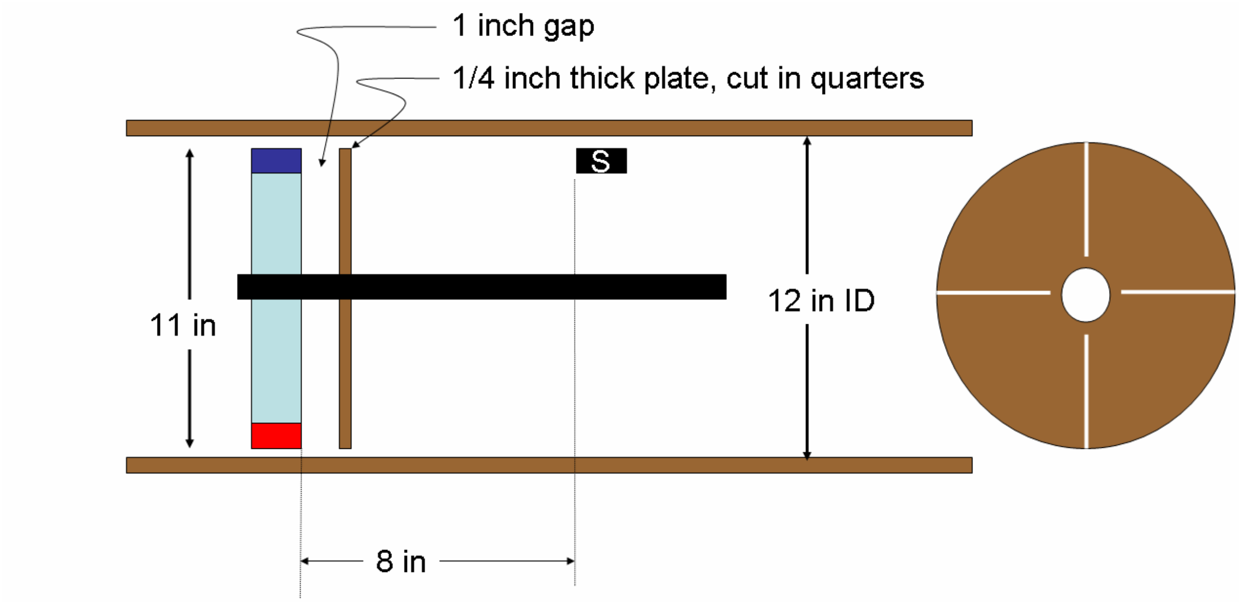

Figure 12. A magnetic shield between the magnet and the sensors to reduce the direct field

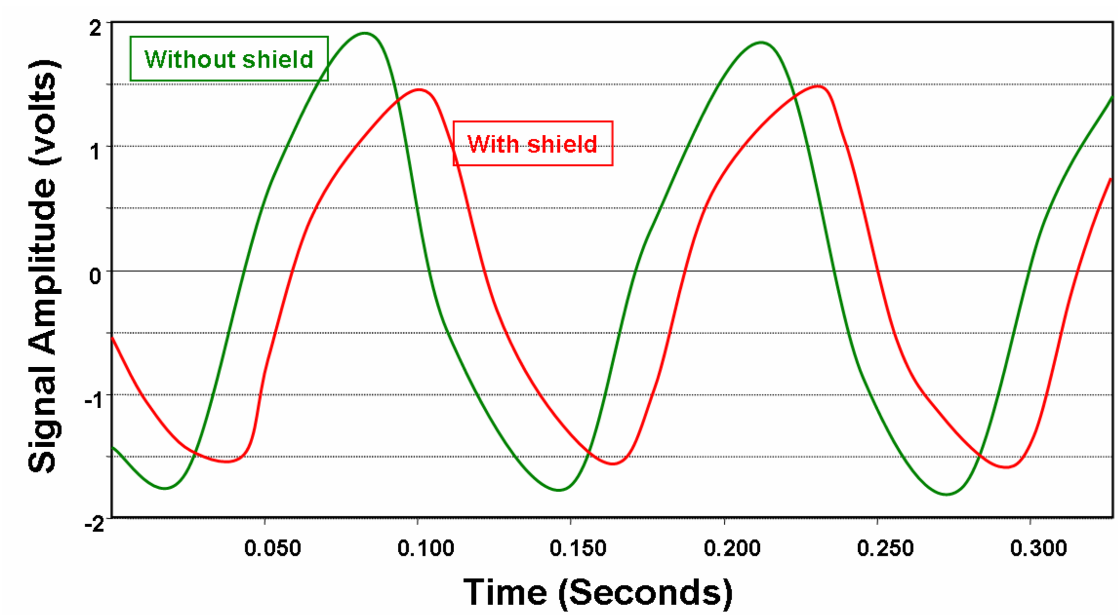

Figure 13. Signal with and without shield designed to reduce the direct magnetic field

Discussion

In the first two years of this project, a new inspection methodology has been developed and demonstrated. The use of moving permanent magnets to generate eddy currents in the pipe wall is an alternative to the commonly used induction coil implementations. Summary of the accomplishments achieved under this project are as follows.

Technology Demonstrated. The capability of this inspection method was demonstrated in blind benchmark tests conducted at Battelle's Pipeline Simulation Facility. The rotating permanent magnet exciter was one of four sensor technologies used to examine corroded 12-inch diameter pipe during a one-week demonstration period in September 2004. The detection and sizing characteristics of the defects used in the benchmark test ranged from simple to difficult. This helped to define both the current capability and future challenges of this inspection technology. The rotating permanent inspection method was able to detect the larger defects and did not make any false calls.

Theory Established. To aid in the development of this new inspection technology, a first order approximation of the field behavior in the rotating magnet system was derived through Ampere's Law and the Law of Charge Conservation. The peak amplitude of the magnetic field as a function of axial position is given by

$$B_{pk}(z) \propto \frac{\beta}{n}\left(\frac{r}{\delta}\right)^2 M_0 e^{-\left(\frac{n}{r}\right)Z}$$

where:

- Z is the distance from the magnets along the pipe
- r is radius
- n is the number of pole pairs
- δ is the classical skin depth
- β is a coupling factor that includes liftoff (between 0 and 1)
- M_0 is magnetic energy in magnet pole piece

This equation indicates that the peak amplitude of the magnetic field is proportional to the magnetizing strength of the pole piece (and the coupling factor) and the square of the ratio of the pipe diameter to classical skin depth, and inversely proportional to the number of pole pieces. Also, the exponential decay constant, given by the ratio n/r, will cause greater decay for smaller pipe diameters and a higher number of pole pieces. This first order approximation suggests that the decay rate is basically geometry dependent. The validity of this equation was demonstrated experimentally.

Signal Processing Implemented. Three signal processing methods were investigated for detection and assessment of pipeline anomalies. A lock in amplifier approach was chosen as the best method for detecting the signals. The lock in amplifier approach has been implemented using commercial off the shelf components. A National Instruments PXI-4472B unit is the fundamental component of the lock in amplifier. It has 8 inputs, a 24 BIT analog to digital converter and a 0.5HZ AC Cutoff Filter. The unit is designed to fit into a PXI instrumentation bus. The PXI communications and lock in amplifier software have been implemented on a standard desktop computer. While this is a bench top implementation, each component can be readily configured for pipeline applications.

Implementation Challenges Addressed. An important feature of this implementation is that the magnet can be configured to a form factor that enables the tool to pass difficult obstructions within the pipeline. Two magnet bar configurations enable the magnets to retract as they pass over obstructions including plug valves.

Implementation variables quantified. Implementation variables such as magnet to pipe separations, sensor location, and rotational speed have been examined. The results will be used in the design of a prototype inspection tool for a 6 to 8 inch crawler system.

Patent Application Completed. A United States patent application has been submitted for this inspection concept. DOE IP Law Division has acknowledged receipt of the disclosure and it has been assigned DOE Case No. S-107,041.

The next step in the program is implementation on a pipeline crawler system. While many design variables are not completely understood, a push towards implementation will illuminate other variables that will have to be addressed. In establishing the initial prototype, inclusion of many potential improvements to this inspection methodology will be deferred to future implementations. With the initial success of this technology demonstrated, and the potential for improvement available, this inspection methodology will see significant improvement in performance capability for the inspection of pipelines that are difficult to pig using currently available technology.

Conclusions

In this second year of a three year development, Battelle continued to develop an electromagnetic sensor system for implementation on pipeline crawlers to inspect pipelines that are currently unpigable with today's technology. This year's efforts focused on refining the rotating permanent magnet system to generate low frequency eddy currents to detect pipeline anomalies. The use of moving permanent magnets to generate eddy currents in the pipe wall is an alternative to the induction coil implementations used by remote field eddy current devices. Rotating permanent magnets create high current densities in the pipe wall that interact with anomalies which allows detection. This electromagnetic sensor technology is targeted toward inspection platforms currently being developed that crawl slowly through a pipeline to maneuver past the physical barriers that currently limit inspection. These devices move down the pipeline independent of the product flow, and even stop for detailed defect assessment. Unlike commercial systems that focus on technologies that work at high inspection speeds, these systems can exploit alternative sensor technologies since inspection speed is not a significant design factor. As such, the rotating permanent magnet system has the potential for inspecting unpigable pipelines since they can be sufficiently small with respect to the bore of the pipe to pass obstructions that limit the application of many inspection technologies.

Specific accomplishments include:

- Demonstration of the rotating permanent magnet technology in blind benchmark tests conducted at Battelle's Pipeline Simulation Facility.

- A closed form equation for designing rotating exciters and positioning sensors was derived from fundamental principles.
- Signal processing methods were investigated for detection and assessment of pipeline anomalies. A lock in amplifier approach was chosen as the best method for detecting the signals.
- Mechanical implementations for passing tight restrictions such as plug valves were investigated.
- A United States patent application has been submitted for this inspection concept.

The goals of the second year of this development have been achieved. The goal the third year is engineering critical components of the rotating inspection system to function with inspection crawlers in a pipeline environment.