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Three Dimensional Mapping of Corrosion Pits in Cast Iron Pipe Using the Remote Field Effect

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ABSTRACT: The remote field effect is an electromagnetic method for inspecting pipes and tubing. It has recently been commercialised as a technique for inspecting gray cast iron and ductile iron water mains. However, commercial tools provide information on pits depths in the pipe and overall wall loss. Models of the mechanical behaviour of cast iron pipe also require information on pit width and length. This paper discusses remote field effect apparatus and experimental techniques used in the laboratory to produce three dimensional electromagnetic field maps. The maps shown in the paper indicate that sizing corrosion pits in three dimensions is possible using the remote field effect. Further research needs are also discussed.

1 INTRODUCTION

The remote field eddy current effect (remote field effect or RFE) has recently been developed into commercially available tools for inspecting cast iron water mains (Staples, 1996). The basic components of the tool include a exciter and one or more receiver coils, both of which are located inside the pipe to be inspected. The exciter coil produces an electromagnetic field which travels to the receiver coil by two paths, one down the centre of the pipe and the other through the pipe wall, into the earth around the pipe and then back through the pipe wall (Figure 1). Provided that the receiver coil is located more than about 2.5 pipe diameters from the exciter coil, the signal travelling outside the pipe is stronger than the inside signal. The outside signal is also sensitive to the thickness of the pipe wall. Thinning of the pipe due to corrosion pitting or general wall loss will change both the amplitude and the phase of the signal. It is this property that allows the technique to be used to detect and measure corrosion pits.

Figure 1. Schematic of the Remote Field Effect

Commercial inspection services report the depth of corrosion pitting in the pipe being inspected. They may also indicate the overall wall loss in the pipe. However, there are two limitations to this type of inspection. First, there is often a minimum pit size below which a pit will not be detected. Secondly and more importantly, pit depth by itself is not necessarily a good indicator of the risk a pit represents to the integrity of a pipe. Robust mechanical models instead require knowledge of at least the pit width and length, if not its actual structure (Rajani and Makar, 2001).

Research at the National Research Council Canada (NRC) has shown that it is possible to use the remote field effect to gather the necessary additional three dimensional information (Rajani, et. al, 2000). This paper presents results from an on-going study aimed at developing a prototype tool that can do three-dimensional measurements in the field. A unique experimental apparatus is described and measurements made on natural and artificial pits in the pipe wall presented. The key characteristics of those measurements that can be used to extract three dimensional pit information are described and the design for the prototype tool discussed.

2 EXPERIMENTAL PROCEDURE

Field use of the remote field effect to inspect cast iron pipe requires that the inspection equipment be placed inside the pipe. This is necessitated both by the nature of the non-destructive evaluation (NDE) technique and its operating environment. A NDE

technique that required access to the outside of buried pipes would not be practical for use by water utilities or other owners of buried services. However, the standard remote field equipment geometry with both exciter and receiver coils inside the pipe is one that is difficult to use in the laboratory, especially when it is desired to produce maps of the electromagnetic fields produced by the exciter coil around corrosion pits or similar pipe damage. Field mapping requires careful positioning of sensors at regular intervals in the area of interest. The constrained geometry inside a pipe makes such careful positioning difficult or impossible to achieve.

The work reported here used an alternate approach first developed by Mergelas and Atherton (Mergelas and Atherton, 1993). In this case the exciter coil is placed inside the pipe as usual, but sensors are placed outside the pipe, above the location of the coil, an arrangement known as the "phantom exciter coil". Figure 1 shows a schematic of the two coil and sensor arrangements. Finite element analysis has shown that phantom exciter geometry produces identical electromagnetic behaviour to the full remote field arrangement where both the exciter coil and the sensors are inside the pipe.

Figure 2 shows a schematic of the experimental apparatus used to produce the results reported here. The major components are a computer, used to control the apparatus and record the experimental measurements, a lock-in amplifier, the coil and sensor systems, the 152 mm pipe being inspected and the positioning system for the sensor. The positioning system used in the experiment is a novel one. Since the goal of the mapping is to investigate the field behaviour at and above the surface of the pipe, it is necessary to be able to move the sensor system in three dimensions. However, three dimensional positioning systems may be expensive and difficult to program to follow the contours of small diameter pipes with the high accuracy required by the experiment. Instead, a machining system was obtained which provided micrometer accuracy in two dimensions. The sensors used in the experiment were placed on an arm attached to the machining jig of the system.

A specially designed rig was then built to hold the pipe inside two aluminum collars. One of the collars was machined with a gear pattern. A stepper motor was attached to the gear to turn the pipe collar and provide the desired third dimension of movement. This part of the system is accurate to within ± 0.5 mm, which is adequate for the needs of the experiment.

This system therefore allows movement of the sensor above the pipe in the axial, circumferential and radial directions (See Figure 2), providing the opportunity for full, three dimensional movement as desired. The sensor system itself consists of three

Hall probes, which are oriented in the axial, circumferential and radial directions. The coil inside the pipe is mounted in a stationary position on a central axial rod in order to ensure that the results were not affected by coil movement as the pipe rotates.

In operation, the internal coil produces a 20 Hz electromagnetic field that interacts with natural or artificial corrosion pits on the pipe's surface. These fields are measured by the sensor array. The output of the three sensors in the array is then amplified in turn by the lock-in amplifier, which is connected to the computer. The computer records the data from the lock-in amplifier and controls the positioning of the sensor array. The results reported here were taken with the sensor array held at a constant distance of 5 mm above the pipe surface.

It should be noted that there is another difference between the experimental apparatus described here and the field equipment. A typical remote field effect inspection in the field places the tool into the pipe and allows it to be carried by water flow to the end of the length that is to be inspected. A cable attached to the end of the tool is then used to pull it back to the entry point at a constant rate. The exciter and receiver coils inside the tool therefore pass under each corrosion pit during the inspection, rather than staying in a stationary position as is the case here. The results shown in Figures 3 to 6 are similar to the measurements that would be expected if the exciter coil was directly below a corrosion pit and an array of sensors was placed in the remote field zone.

Analysis of the field plots provides another difference. Since they are one dimensional, amplitude and phase can be combined in a single polar plot. This helps to bring out the presence of the defects because both characteristics are changed. This type of combination plot is impossible with the two dimensional plots shown here, making separate graphs of the phase and amplitude changes necessary. The authors hope to develop an approach to combining the two parameters in a single two-dimensional plot in order to ease interpretation of these results in the future.

The research reported here included measurements from both natural corrosion pits and flat bottomed, milled cylindrical holes. Only examples of the latter are shown in this paper. The milled pits were produced in order to create controlled defects in the pipe which would allow for easy comparison between the pit shape and the measured fields. Earlier work (Rajani, et. al, 2000) using a precursor of the current apparatus had shown that two dimensional mapping of the electromagnetic fields was possible, but did not provide enough information to determine if accurate sizing of the pits could be attained. The new apparatus and controlled pit sizes permits this determination.

Figure 2 – Apparatus Schematic

3 EXPERIMENTAL RESULTS

Figures 3 to 5 show the radial, circumferential and axial components of the electromagnetic field perturbations produced by a 20 mm diameter, 6 mm deep flat pit milled into the side of the test pipe. For these results the exciter coil inside the pipe was placed directly under the pit in order to simulate the equivalent field situation, where the remote field exciter coil is passing under a real corrosion pit. Figures 3a, 4a and 5a show the amplitude of the field (contour units are in Tesla), while figures 3b, 4b and 5b show the phase (contour units are in degrees). Similar results were seen for the other milled pits and for the measurements made on true corrosion pits. The circle shown in each figure indicates the location of the milled pit.

The radial component of the field amplitude in Figure 3a shows both a peak in the field and a steep field gradient in the axial direction across the milled pit. The peak in the field appears to take place close to the edge of the pit. However, there is very little change in the field behaviour across the pit in the circumferential direction, making it difficult to obtain information about pit dimensions in this direction. A similar difficulty is observed in Figure 4b. While there is a distinct peak in the phase of the radial component of the field on the left hand side of the milled pit, much of the phase behaviour is concealed by the rapid change in phase created by the location of the exciter coil directly below the pit. There is little or no difference in the phase behaviour across the pit in the circumferential direction.

The circumferential field components in Figure 4 show more complex behaviour. In Figure 4a, the circumferential field shows two peaks (along the $x=y$ line of the graph) and two minimums (along the $x=-y$ line of the graph). The size of the circumferential field change produced by the milled pit is smaller than that observed for the axial or radial components. In contrast, the phase changes are much larger than those shown for either of the other two components for this particular coil position. The largest change in the axial phase is approximately 10° , while the radial component phase change is approximately 8° . The circumferential phase change shown in the graph has a maximum value of 60° . It is interesting to note that the maximum amplitude change for this component occurs along the $x=y$ line, while the maximum phase change occurs along the $x=-y$ line.

Both Figure 5a and 5b show distinct axial amplitude and phase peaks centered about the milled pit. Each parameter also shows relatively small changes in the central area of the pit, with a significantly more rapid gradient outside the pit perimeter. The

two plots are very similar in appearance, unlike either the circumferential or radial results, where the phase and amplitude do not show a strong correlation.

Figure 6 shows the radial component of the field at the same pit, but with the exciter coil placed away from the pit in order to simulate the field perturbations created as the exciter coil approaches or leaves the pit. The field configurations are noticeably different between this Figure and that in Figure 3. The amplitude component shows a minimum value in the location of the corrosion pit which is similar in nature to that of Figure 5 for the axial component, while the phase shows a maximum on the left hand side of the milled pit and a minimum on the right hand side of the pit. The change in amplitude and phase of the field have approximately the same magnitude as the changes shown in Figure 3.

4 DISCUSSION

It is clear from the data shown in Figures 3 to 6 that enough information can be recorded from the fields around the pit to determine its approximate dimensions. The depth of the pit can be determined from the magnitude of the observed amplitude and phase changes, while the distribution of those changes in terms of gradients can be used to estimate the length and width of the pit. When the exciter coil is located directly under the corrosion pit, measurements of the axial component of the field appear to be most useful as both the amplitude and phase parameters have strong peaks centered about the pits. The radial field and phase components appear to produce a similar level of information when the exciter coil is located a short distance away from the pit. Three dimensional sizing of corrosion pits in in-service water pipes is therefore physically possible.

However, a number of research and development questions need to be resolved before such an inspection technique can be implemented commercially. The experimental techniques reported here are clearly inappropriate for use in the field, where all of the measurements need to be taken at the same time as the inspection tool is pulled along the pipe. The results here suggest that the use of a number of small sensors placed around the interior circumference of the pipe would provide equivalent information. These sensors would likely need to be in the form of coils, rather than Hall probes in order to minimize the cost of the apparatus. However, the spacing and exact number of sensors required for the tool needs to be established. The results shown here show that the field perturbations produced by the corrosion pit do not, in general, extend a significant distance away from the location of the pit. While changes in the

fields in the axial direction may be easy to detect by
a single coil, changes in fields in the circumferential

Figure 3. Radial field component with coil centered on 20 mm pit: top, Figure 3a, field amplitude (mTesla), bottom, Figure 3b, field phase (degrees)

Figure 4. Circumferential field component with coil centered on 20 mm pit: top, Figure 4a, field amplitude (mTesla), bottom, Figure 4b, field phase (degrees)

Figure 5. Axial field component with coil centered on 20 mm pit: top, Figure 5a, field amplitude (mTesla), bottom, Figure 5b, field phase (degrees)

Figure 6. Radial field component with coil centered away from 20 mm pit: top, Figure 6a, field amplitude (mTesla), bottom, Figure 6b, field phase (degrees)

direction require either large coils that cover all or a significant part of the circumference of the pipe (the current situation) or more numerous small sensors that can measure local fields. The spacing of the smaller sensors will therefore control both the size of the corrosion pits that can be detected and the accuracy with which they can be measured. As an example, sensors placed at a 10 mm spacing would clearly be capable of measuring the axial fields produced by the 20 mm diameter pit shown in Figures 3 to 6 and producing an estimate of its size. Such an array would measure a strong field change at the centre of the pit, a slightly weaker maximum field at each edge of the pit, significantly weaker fields at 10 mm from the pit edge and background fields at 20 mm from the pit edge. The gradient of the measured fields in axial direction would produce information on the size of the pit in that direction. Coils arranged to take measurements in the circumferential or radial directions could be used to confirm the measurements and improve the accuracy of the overall estimate of the corrosion pit size. Reducing the spacing of the coils would increase the accuracy of the measurements and allow detection of smaller pits.

However, there are several problems with such an approach. The first is the additional cost of making these measurements. This includes not only the cost of the additional coil sensors, but also that of the associated electronics and, more importantly, the analysis of the data. Most NDE analysis is performed by human operators, possibly with some software assistance. Analysing data from a much higher number of sensors would therefore require significantly more resources than from a single sensor system. This difficulty may be addressed by the development of clearer ways of presenting the data and by the creation of pattern recognition systems based on artificial intelligence software for the identification of signals from corrosion pits in pipes. The cost of the additional electronics and sensors would remain, but this cost could be offset by the more efficient data analysis process.

A second question is the size of corrosion pit that should be targeted by the NDE technique. While research has indicated that more than 90% of failures in small diameter pipes are associated with corrosion pits, the influence of corrosion pitting on the mechanical resistance of the pipe to failure is still unknown. Recent work at NRC has suggested that corrosion pits have an influence on pipe strength itself, rather than simply through the reduction of pipe wall thickness and the creation of stress concentrations. Further research is underway to confirm this effect, to explain it and to look at the effect of corrosion pitting on the mechanical strength of full pipe samples. This research should indicate the size of corrosion pit that should be targeted by future remote

field effect inspection tools, which will help to determine the necessary sensor distribution in future field tools.

A final issue that needs to be explored is the effect of the radial location of the sensors within the pipe. The measurements shown here were made close to the pipe surface on the outside of the pipe. Measurements in the field will not only be made on the inside of the pipe in the remote field zone, but will also be placed a significant distance from the interior pipe surface. Cast iron water pipes may contain significant tuberculation, which can impede or prevent the movement of the remote field inspection tool along the pipe. Inspection is normally preceded by cleaning, but only to the point where a 126 mm tool can pass through a 152 mm pipe. The sensor array is therefore highly unlikely to be located immediately adjacent to the interior pipe surface. Further work is therefore required to understand the effect of sensor location within the pipe on the ability to accurately size corrosion pits.

5 CONCLUSIONS

The results of the study shown here show that it is possible to size corrosion pits with respect to length and width as well as depth using the remote field effect. This type of measurement should add significant additional value to a remote field inspection, since the information produced can be used to determine the residual strength of the pipe using mechanical modeling. This approach should enable water utilities to make better decisions about the repair, rehabilitation or replacement of pipelines. However, significant research remains to be done before the full potential of this technique can be achieved. This research includes pattern recognition software, improved understanding of the influence of the mechanical behaviour of cast iron pipes and the development of prototype tools that will allow investigation of the impact of sensor location inside the pipe on the accuracy of the investigations.

The additional value provided by the ability to size corrosion pits is likely to make remote field inspection more attractive to the industry as a management tool. Other important factors for increasing industry take up of the technology include lowering the costs of each inspection and developing robust management models to enable water utilities to use the information produced by the tool. Economic modeling that shows the advantages of the technology and concrete examples of money saved using remote field inspection are likely to provide the most convincing arguments for its use.

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