An In-Tube Radar for Detecting Cracks in Metal Tubing

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Abstract
A major cause of failures in heat exchangers and steam generators in nuclear power plants is degradation of the tubes within them. The tube failure is often caused by the development of cracks that begin on the outer surface of the tube and propagate both inwards and laterally. A new technique will be described for detection of defects using a continuous-wave radar device within metal tubing. The technique is 100% volumetric, and may find smaller defects, find them more rapidly, and find them less expensively than present methods. Because this project was started only recently, there is no demonstrated performance to report so far. However, the basic engineering concepts will be presented together with a description of the milestone tasks and dates.

Introduction
The basic idea is to transmit, from within the tube, an electric field which is parallel to the axis of the tube. The field, after first reflecting off the interior wall, will propagate into the wall, reflect off an anomaly, and return to an internal receiver. A pulse-type radar system cannot be used because of the combination of the small inner diameter and large conductivity of heat exchanger tubes. Instead, a continuous-wave, ground penetrating, borehole radar is adapted to the examination of metal tubes.

Continuous-Wave Radar
The inherent difficulty with continuous-wave radar is that the signal from the transmitter may be coupled directly to the receiver and overwhelm the much smaller return signal from an anomaly. This ‘crosstalk’ can be reduced by locating the receiving antenna in a portion of the transmitter field where the field is a minimum. The in-tube radar concept uses the electric field from a magnetic dipole antenna so that a null occurs along the
centerline of the tube. The magnetic dipole is formed by a small, multi-turn loop that is centered on the centerline of the tube. The windings are parallel to the \( yz \)-plane, and the winding-axis is oriented along the \( x \)-axis. The \( z \)-component of the electric field from this '\( x \)-directed' dipole is given by:

\[
E_z = j \mu \omega M \sin \theta \sin \phi \left( 1 - jkR \right) \exp(jkR)/R^2,
\]

and is parallel to the inner wall of the tube. The volume distribution of the magnitude of the electric field resembles two spheres that are tangent at the origin of coordinates as shown in Fig. 1. The \( E_z \) field is zero on the \( z \)-axis, and the two lobes in the field pattern are out of phase with each other. A cylindrical electric dipole with a non-zero radius, located both along and parallel to the \( z \)-axis, will have minimum crosstalk from the transmitter.

Figure 1. Relative Magnitude of the \( E_z \)-field from an \( x \)-directed Magnetic Dipole in a Homogeneous Medium
Receiver Location in a Metal Tube

Figure 1 is drawn for the transmitting magnetic dipole in an unbounded medium: The $E_Z$-field is just the primary field from the transmitter. However, both the transmitter and receiver are within a metal tube, and the total field, including the reflection from the tube wall, must be considered. Where should the receiving dipole be located to minimize crosstalk for this case? As a specific example, consider an Inconel tube with an ID of 2.2cm [0.866 inches], a wall thickness of 0.127cm [0.050 inches], and a conductivity of 8.2E5 S/m [resistivity = 122 μΩ-cm]. The frequency is chosen as 47.88kHz, as described in a report (2), and the distribution of the $E_Z$-field within the tube is computed from (3) and shown below.

![Figure 2. Relative Magnitude of the Total $E_Z$-field within a 2.2cm Inconel Tube at $z = 2.2$cm or One Inner Diameter](image)

The $E_Z$-surface appears as a folded disc, curved slightly downward at the outer edge that corresponds to the inner wall of the tube. There is an undulation close to each side of the $y$-axis which falls to zero at the center and at $y = \pm 1$. It still appears that an electric dipole, located on the axis, will have minimal crosstalk from the transmitter because the two halves of the pattern are out of phase with each other.
The actual transmitting antenna consists of both x- and y-directed magnetic dipoles that are driven alternately. The received voltages are separately recorded, and then processed in software to synthetically rotate the transmitter beam in the $xy$-plane to examine the entire cylindrical volume of the tube wall.

If, however, the $z$-axis of the coordinate system is either tilted or displaced from the centerline of the tube, the crosstalk will increase. The computation of both crosstalk and backscatter from anomalies under these asymmetric conditions, and the mechanical design to limit asymmetry within useful minimum ratios of signal-to-crosstalk, are the major computational, design, and manufacturing challenges.

**Computational Milestone**

The examination of the crosstalk due to asymmetric antenna location within the tube is being pursued by two approaches at NMSU. Crosstalk is being computed with the Sandia code CTUBE based on (3), which is a boundary-value problem using an offset source in cylindrical coordinates. A comprehensive modeling approach, that computes both crosstalk within the tube and backscatter from different types of anomalies, is also underway at NMSU using a hybrid Finite Element and Method of Moments code (4). Another 3D approach is being computed at Sandia using a suite of codes that were developed in Russia under an IPP contract. These codes solve the vector Helmholtz equation by the conjugate gradient method with iterative sequential application of both the thinning method and the Lanczos method to reduce the size of the problem matrix (5). Extensive results will be available in November 2000 from Sandia, and in December 2000 from NMSU, that will indicate tilt and offset limits for adequate signal-to-crosstalk ratio for a suite of typical anomalies.

**Design Milestone**

All aspects of design, fabrication, and testing are being performed at NMSU with the assistance of two graduate students and nine undergraduates under the guidance of the professional staff. Work tasks include mechanical and thermal design, electronic and fiber-optic design, and software development for package control, data collection, signal processing and display. Several of these tasks are also directed at the fabrication of a scaled-up, 4X, prototype that will be used for design verification. Significant effort is being devoted to the design of centering concepts in both straight and curved tubing that can also respond to a change in diameter or the presence of sleeve inserts. Electronic design is proceeding with particular emphasis on miniature electro-optic components and batteries. It is planned to use MatLab as a postprocessor for signal analysis and graphical display, and the interface software development has begun. Several of the design problems are being pursued by students as part of a senior-level capstone course. A product development schedule for the prototype probe will also be available in December 2000.

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1 IPP is the USDOE Initiative for Proliferation Prevention that provides scientific work for staff members at former nuclear weapon facilities in Russia. These codes were written by a team at the Russian Federal Nuclear Center, All-Russian Scientific Research Institute of Theoretical Physics (VNIITF) at Snezhinsk under the direction of G. A. Newman of Sandia.
System Testing Milestone
The EM computations and the product development schedule will be integrated into a fabrication and testing program at the Advancement Manufacturing Center at NMSU in December 2000. A progress report that includes descriptions of all design elements together with measured performance characteristics should be ready in November 2001.

Industrial Demonstration Milestone
Refinements of the initial system will no doubt be necessary, and when they are installed and verified, a schedule of demonstrations to industrial users will begin in July 2002. The program will conclude with a final report to be published in February 2003 after demonstrations at EPRI-NDE.

EPRI-NDE Involvement
The collaborative assistance of EPRI-NDE is on a verbal basis, and EPRI-NDE does not receive funding from the USDOE. Information that EPRI provides is a valuable guide to the performance requirements that must be met by the In-Tube Radar in order be of interest to the nuclear/electric industry. The assistance of EPRI does not constitute an endorsement of the In-Tube Radar. We thank Gary Henry, Kenji Krzywosz, Larry Cagle, and Nathan Muthu for their instruction and informative discussions during our visit to EPRI-NDE in January 2000.

References


