HIGH-POWER LONG-RANGE GUIDED-WAVE INSPECTION OF PIPELINES

FINAL REPORT
Other Transaction Agreement DTRS56-03-T-0013
SwRI Project 14.10062

Prepared for

Pipeline and Hazardous Materials Safety Administration
U.S. Department of Transportation
United States Government

Prepared by

Sensor Systems and NDE Technology Department
Applied Physics Division

DISTRIBUTION STATEMENT. Distribution authorized to U.S. Government agencies only to protect information protected by a contractor's "limited rights" statement, or received with the understanding that it will not be routinely transmitted outside the U.S. government. Other requests for this document are to be referred to the Technical Manager.

August 2005

SOUTHWEST RESEARCH INSTITUTE

SAN ANTONIO HOUSTON
DETROIT WASHINGTON, DC

HIGH-POWER LONG-RANGE GUIDED-WAVE INSPECTION OF PIPELINES

FINAL REPORT
Other Transaction Agreement DTRS56-03-T-0013
SwRI Project 14.10062

Prepared for

Pipeline and Hazardous Materials Safety Administration
U.S. Department of Transportation
United States Government

Prepared by

Sensor Systems and NDE Technology Department
Applied Physics Division

August 2005

Written by
Hegeon Kwun, Ph.D.
Staff Scientist
Sang Y. Kim, Ph.D.
Senior Research Scientist

Approved by
Glenn M. Light, Ph.D.
Director

TABLE OF CONTENTS

Page

1. INTRODUCTION 1

1.1 Pipelines and the Pipeline Safety Improvement Act of 2002 1

1.2 Pipeline Assessment Methods 1

1.3 R&D Needs for Pipeline Assessment Technologies 2

1.4 Objective of the Subject Project and Overall Achievement/Findings 2

1.5 Outline of the Report 3

2. TECHNICAL BACKGROUND 4

2.1 Long-Lange Guided-Wave Inspection of Piping 4

2.2 Guided-Wave Mode Used for Long-Range Piping Inspection 4

2.3 The Magnetostrictive Sensor (MsS) Technology 5

2.4 Issues Related to Inspection of Coated/Buried Pipelines and Improvement Needs 7

3. HIGH-POWER MsS DEVELOPMENT 8

3.1 Technical Objective and Approaches 8

3.1.1 Technical Objective, Target Goal, and Test Range Extension 8

3.1.2 Previous MsS Specifications and Technical Approaches for Enhancing Power 8

3.2 Evaluation of Power Enhancing Approaches 9

3.2.1 Sensor Optimization 9

3.2.2 Multiple Sensor Pairs 13

3.2.3 Better Strip Materials 14

3.2.4 Summary 15

3.3 Other Improvements 16

3.3.1 Time-Controlled Gain 16

3.3.2 Calibration 17

3.3.3 Dry-Coupling Method 19

3.3.4 Discrimination Between Weld and Defect Signals 20

TABLE OF CONTENTS

Page

TABLE OF CONTENTS

Page

4. FIELD TEST RESULTS AND FINDINGS 22

4.1 General 22

4.2 Inspection Capabilities on Aboveground Straight Pipelines 22

4.3 Inspection Capabilities on Buried Pipelines 26

4.4 Other Factors That Limit Inspection Capabilities 29

4.5 Summary 29

5. CONCLUSIONS AND RECOMMENDATIONS 32

5.1 Conclusions 32

5.2 Recommendations 32

6. ACKNOWLEDGMENTS 34

7. REFERENCES 34

LIST OF FIGURES

Figure		Page
1	Long-range guided-wave inspection of piping	4
2	Examples of dispersion waves of various guided wave modes in pipe (for 4.5-inch-OD, 0.339-inch-thick pipe). The numbers in parentheses indicate the order of the wave mode.	5
3	MsS system for piping inspection	6
4	Strips bonded on a pipe (a) and MsS ribbon coils placed over the strips (b)	6
5	Table of attainable extension in test range with a 20-fold increase in signal amplitude	8
6	Dependence of signal amplitude on the strip width relative to wavelength	9
7	Dependence of signal amplitude on the strip thickness (material: nickel 201)	10
8	Relationship between the applied current in the MsS coil, excitation frequency, and coil diameter	11
9	Signal amplitude versus the excitation voltage: 100-percent MsS transmitter output corresponds to 300 volts peak-to-peak excitation voltage. The data are from 16-inch-OD pipe.	12
10	Signal amplitude obtained using different numbers of sensor pairs	13
11	Photo of three pairs of strips installed on a 16-inch-OD pipeline sample (strips are hidden below the duct tape)	14
12	Physical properties of Hiperco 50HS and annealed nickel 201	14
13	Comparison of signal amplitudes obtained using Hiperco 50HS and annealed nickel 201 strips	15
14	Comparison of data acquired from an aboveground 125.5-foot-long, 6-5/8-inch-OD, bitumen-coated pipeline sample with (bottom) and without (top) TCG	17
15	A hose clamp placed around a 20-inch-OD line for calibration purposes	18
16	Reflection coefficients of hose clamp placed on various pipe sizes	18
17	Photo of the dry-coupling arrangement for pipeline testing	19
18	32-kHz T-mode data obtained from a 12-inch-OD pipe using the dry-coupling method	20

LIST OF FIGURES

Figure **Page**

19 Incident and reflected signals from a step-wise change in pipewall thickness....21

20 32-kHz T-mode data obtained from a 16-inch OD aboveground straight pipeline....22

21 A photo of 16-inch OD gas transmission line and MsS test setup....23

22 Processed data of the 32-kHz T-mode data in Figure 19....24

23 32-kHz T-mode data from a 10-3/4-inch cased line. MsS location at about 320 feet; m1, m2 – highway casing ends; M1, M2 – road casing ends; w, W – welds; sp, SP – spacers; ps – pipe support; R – clamp reference (equivalent to 2-percent defect in this case); RO – roller; MW – miter weld....24

24 Photo of 10-3/4-OD cased pipeline (left) at road crossings....25

25 Photo of a spacer used on the cased section of pipelines....26

26 32-kHz data from a 24-inch-OD buried pipeline with a fusion-bonded-epoxy coating....26

27 Test setup on the 24-inch-OD flow loop at PSF....27

28 16- and 32-kHz data acquired from a buried, bitumen-coated, 22-inch-OD pipeline....28

29 MsS setup on a 22-inch bitumen-coated pipeline in a bell hole....28

30 Photos of various line features: (a) and (e) roller; (b) pipe support sleeve; (c) and (d) clamp with fiberglass jacket; (f) branch piping....30

31 32-kHz T-mode data obtained from a 14-inch-OD straight aboveground pipeline built in the early 1940s. The guided waves were reflected mostly from both ends of a 40-foot pipe joint and reverberated in the pipe joint. Poor welded joints at both ends were believed to be the cause....31

1. INTRODUCTION

1.1 Pipelines and the Pipeline Safety Improvement Act of 2002

In our nation, there are more than 2.3 million miles of pipelines that transport natural gas, oil, or petrochemical liquids. Being the safest and least costly means of transporting these products, the pipelines are a vital infrastructure for our national economy, security, and well-being. Pipeline incidents/accidents not only interrupt the supply and distribution of these energy products and, thus, impact the national economy, but can also cause severe damage to human health, property, and the environment. Maintaining the structural integrity and safe operation of the pipelines is, therefore, of national interest.

Recognizing the importance of ensuring the safety and integrity of the pipelines, Congress passed the Pipeline Safety Improvement Act in 2002 (PSIA 2002), which was signed into law on December 17, 2002.

Mandated by PSIA 2002, the Office of Pipeline Safety (OPS), Research and Special Programs Administration (RSPA), now the Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation (DOT), on December 15, 2003, issued the final ruling on 49 CFR Part 192, Pipeline Safety: Gas Pipeline Integrity Management in High-Consequence Areas (HCA). Accordingly, all operators of gas transmission lines are required to develop and implement an Integrity Management Program (IMP).

Key requirements of the IMP include: (1) identify HCA on pipeline systems each operator owns, (2) conduct risk analyses of these areas, (3) perform baseline integrity assessments of each pipeline segment, and (4) inspect the entire pipeline system according to a prescribed schedule and using prescribed methods. Key timetables for the operators to follow are: (1) identify all HCA and submit specific IMPs to OPS by December 17, 2004, (2) inspect all pipeline segments within HCA and complete remediation plans (if required) by December 17, 2008, and (3) finish baseline inspection and assessments of non-HCA segments by December 17, 2012. All segments must be reinspected every 7 years, with certain exceptions. Extensive information on this subject is available from OPS's website: http://ops.dot.gov.

1.2 Pipeline Assessment Methods

The ruling on Pipeline Safety: Gas Pipeline Integrity Management in High-Consequence Areas identifies three primary methods for assessing the line integrity: in-line inspection (ILI), hydrostatic pressure testing, and direct assessment (DA).

The ILI method can be applied only to those pipelines that are designed for inspection with "smart pigs." These "piggable" lines comprise approximately 25 to 30 percent of the nation's pipelines. Retrofitting "unpiggable" lines for ILI is too costly and unjustifiable, considering that HCA constitute only segments of a pipeline.

The hydrostatic pressure testing involves filling a line with water and testing the leak-tightness of the line at a prescribed pressure (in excess of the maximum operating pressure of the line being tested) and for a prescribed duration. This method is widely used on hazardous liquid pipelines, but is not preferred for gas pipelines.

The DA method is a structured assessment process that utilizes physical characteristics and the operating history of a pipeline, together with the results of various diagnostic testing performed on the line, to determine the line's integrity. DA is used to evaluate the risks of three time-dependent threats to the integrity of a pipeline segment: external corrosion (EC), internal corrosion (IC), and stress corrosion cracking (SCC). DA effectiveness is validated through indirect and direct examination of the pipeline segment for its conditions.

Further information on assessment methods can also be found at the OPS website: http://ops.dot.gov.

1.3 R&D Needs for Pipeline Assessment Technologies

To improve and assure the safety and integrity of the nation's pipeline infrastructure, R&D of new or improved pipeline assessment technologies is necessary for use in IMP. Recognizing the R&D need, RSPA (now PHMSA) began funding R&D programs selected through Broad Agency Announcements (BAAs) in 2002. The R&D programs are focused on specific areas that are identified as key for achieving the pipeline safety goals. These key areas include damage prevention, leak detection, enhanced pipeline operations, controls, and monitoring, as well as other pipeline safety improvements such as strengthening/validating DA practices and developing new or improved direct/indirect inspection technologies.

This project is one of the projects selected from an RSPA BAA in 2003 and is aimed at improving the capability of the long-range guided-wave inspection technology for internal corrosion direct assessment (ICDA) and external corrosion direct assessment (ECDA).

1.4 Objective of the Subject Project and Overall Achievement/Findings

The objective of this project was to increase the guided wave power of the magnetostrictive sensor (MsS) technology so that the test range of guided wave achievable on pipelines could be further extended. The target goal of the project was a 20-fold (or 26-dB) increase in the guided-wave signal amplitude. The extension in the test range attainable by the 20-fold increase in the guided-wave signal amplitude depends on the wave attenuation coefficient, α, of the pipeline under testing and is equal to $26/(2\alpha)$, where the factor 2 accounts for the round trip. For example, for α = 2.0 dB/ft, the extension in the test range is 6.5 feet; for α = 1.0 dB/ft, 13 feet; for α = 0.5 dB/ft, 26 feet; for α = 0.25 dB/ft, 52 feet; for α = 0.1 dB/ft, 130 feet; for α = 0.05 dB/ft, 260 feet.

The project target goal was successfully achieved through the combined use of a better magnetostrictive material, sensor optimization, and multiple sensors. As a result of the improvement, the test range of more than 500 feet in one direction was achieved in the field for detection of 2- to 3-percent defects in straight aboveground pipelines, where α was relatively low (0.02 to 0.05 dB/ft). In comparison, the typical test range achievable before the improvement in straight aboveground pipelines was about 100 feet in one direction. On buried pipelines in the field, however, the achievable test range using the high-power MsS was found to be no more than 20 to 30 feet in one direction for detection of 20-percent defects. The short test range was attributed to the unexpectedly high α (more than 2 dB/ft) exhibited by the buried lines in the field. Because of the high attenuation, the extension in the test range achievable with the increased power was

only a few to several feet, an insignificant amount for meriting wider usage of the guided-wave technology for DA of buried lines.

Based on the findings from field evaluations, the following conclusions were reached.

(1) Considering the short test range achievable and the high cost for excavation required, the guided-wave technology has limited usefulness for DA of buried pipelines.

(2) The guided-wave technology is best used for DA of pipelines that have low wave attenuation (for example, aboveground lines) to moderate wave attenuation (for example, cased lines at road crossings).

(3) Initial guided-wave survey followed by periodic long-term condition monitoring with permanently installed guided-wave probes would provide an effective DA of pipeline sections in an HCA (for example, cased section of lines at a highway road crossing).

1.5 Outline of the Report

Technical background on long-range guided-wave inspection of piping and the MsS technology used in this project is described in Section 2. The technical approaches used to increase the guided-wave power and the technical achievement attained in this project are provided in Section 3. Field test results of the high-power MsS guided wave are presented in Section 4, together with the capabilities and limitations. Overall conclusions and recommendations for the follow-on work are given in Section 5.

2. TECHNICAL BACKGROUND

2.1 Long-Lange Guided-Wave Inspection of Piping

The long-range guided-wave inspection is an emerging technology for direct examination of piping for internal and external corrosion defects [1,2]. It involves installing a guided-wave probe around the pipe circumference being tested, launching a pulse of guided waves along the pipe, and detecting signals reflected back from defects and welds, as illustrated in Figure 1.

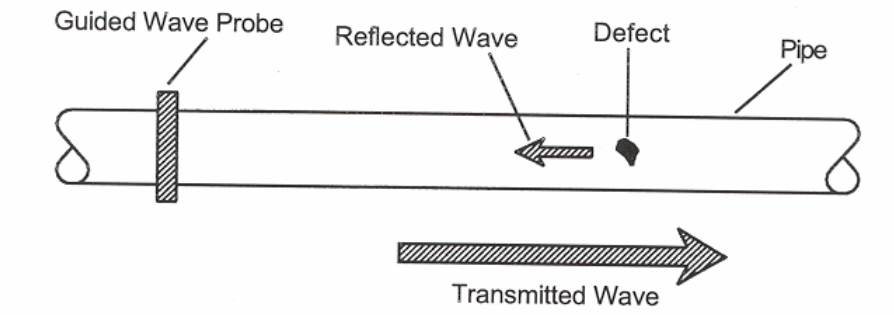

Figure 1. Long-range guided-wave inspection of piping

From a given test position, the technology can survey a long length of piping on-line and locate defects present in the line. In aboveground straight piping, the range of inspection is typically more than 100 feet in one direction for detection of 2- to 3-percent defects (here, percent refers to the circumferential cross-sectional area of a defect relative to the total pipewall cross section). The axial location (within ±6 inches) and severity of a defect are determined from the timing of the defect signal and the signal amplitude. This technology is now widely used for inspection of piping networks in processing plants such as refineries and chemical plants.

Because of its long-range inspection capability, the guided-wave technology is particularly useful for inspecting inaccessible areas from a remote accessible position. The pipeline operators recognize this technology as an important tool for ECDA and ICDA applications, particularly for the inaccessible length of cased lines for which other potential DA tools (such as the NoPig® aboveground metal loss measurement technique [3]) cannot be applied due to interference from the casing pipe.

2.2 Guided-Wave Mode Used for Long-Range Piping Inspection

There are primarily three types of guided-wave modes in a pipe—Longitudinal (L), Torsional (T), and Flexural (F). The L-modes are a compressional wave and have axial and radial displacements. The T-modes are a shear wave and have circumferential displacements. The F-modes are similar to the vibrational motion of a string and have displacements in all three directions (axial, radial, and circumferential). Properties of these waves are somewhat complex and vary significantly with pipe diameter and wall thickness [4,5]. To illustrate their wave propagation properties, examples of their dispersion curves are shown in Figure 2. All L- and F-modes show wave dispersion; namely, varying velocity with frequency. The T(0,1)-mode, on the other hand, has a constant velocity, independent of frequency.

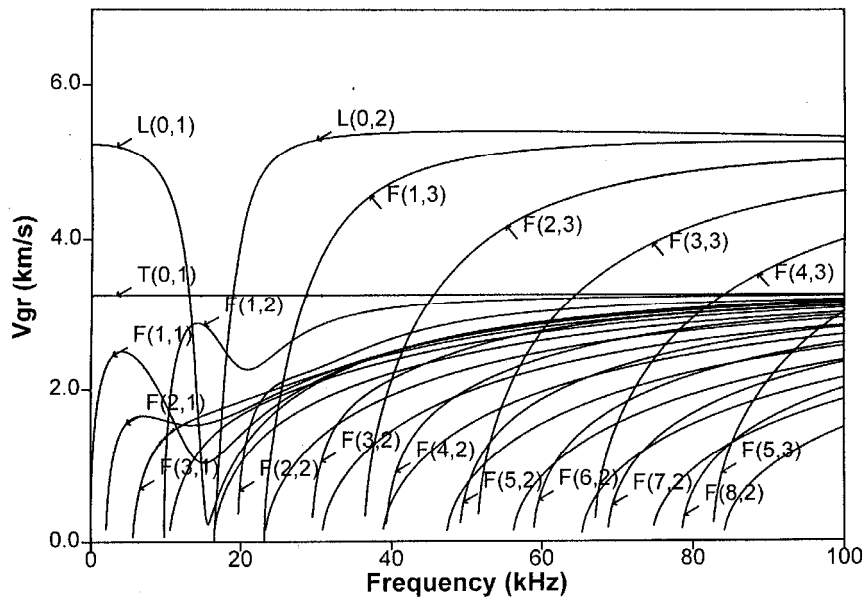

Figure 2. Examples of dispersion waves of various guided wave modes in pipe (for 4.5-inch-OD, 0.339-inch-thick pipe). The numbers in parentheses indicate the order of the wave mode.

For long-range inspection, use has been made of both L- and T-modes. Because the T-mode is dispersion-free, not adversely affected by the presence of liquid in pipe, and less prone to generate extraneous wave modes, it is the preferred guided-wave mode for piping inspections.

2.3 The Magnetostrictive Sensor (MsS) Technology

The MsS technology is a guided-wave technology developed and patented by SwRI [2]. The MsS generates and detects guided waves electromagnetically in the material under testing. For wave generation, it relies on the magnetostrictive (or Joule) effect; the manifestation of a small change in the physical dimensions of ferromagnetic materials—on the order of several parts per million in carbon steel—caused by an externally applied magnetic field. For wave detection, it relies on the inverse-magnetostrictive (or Villari) effect, the change in the magnetic induction of ferromagnetic material caused by mechanical stress (or strain). Since the probe relies on the magnetostrictive effects, it is called a "magnetostrictive sensor (MsS)." In comparison, other guided-wave systems developed in England for piping inspection (Teletest® and Wavemaker®) use a guided-wave probe that consists of an array of dry-coupled piezoelectric transducers arranged in a ring-shaped device [1].

Figure 3 illustrates the MsS system used for T-mode piping inspection. The T-mode MsS guided-wave probe consists of thin strips of magnetostrictive material (typically nickel) bonded to pipe around the circumference and a quick install/uninstall encircling coil (consisting of ribbon coil and a coil adapter) placed over the strips. For control of wave direction, two MsS guided-wave probes are used for piping inspection. For T-mode operation, the strips bonded around the pipe are magnetically conditioned. This involves inducing residual magnetization in the strip along its lengthwise direction by passing a permanent magnet over the strip around the pipe. A picture of the strips bonded on a pipe and the MsS ribbon coils placed over the strips is shown in Figure 4.

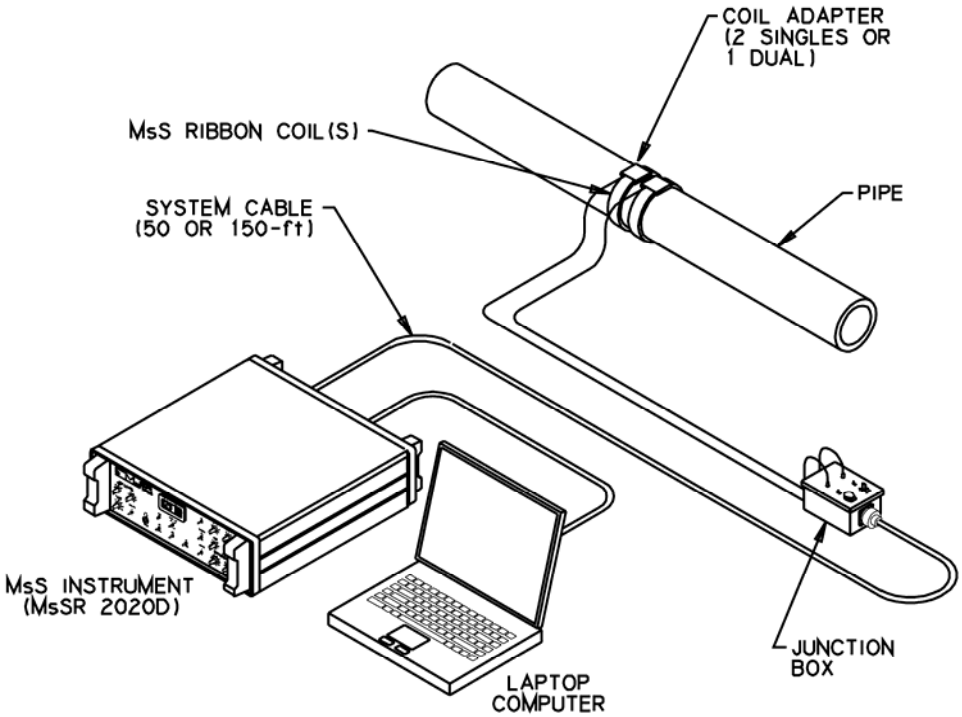

Figure 3. MsS system for piping inspection

(a) (b)

Figure 4. Strips bonded on a pipe (a) and MsS ribbon coils placed over the strips (b)

2.4 Issues Related to Inspection of Coated/Buried Pipelines and Improvement Needs

As described in Section 2.1, the guided-wave technology can inspect long sections of pipeline—typically, more than 100 feet from the sensor in either direction in aboveground straight pipe for detection of 2- to 3-percent internal and external defects using 30- to 40-kHz T-mode. In coated and/or buried pipelines, the wave attenuation is much higher than in the aboveground bare or painted pipelines. For example, the attenuation coefficient of 30-kHz T-mode is typically less than 0.05 dB/ft in aboveground bare/painted pipelines and 0.3 to over 1 dB/ft in coated/buried pipelines, depending on the coating type, soil depth, soil type, soil compaction, etc. Consequently, the test range on coated/buried lines is significantly shorter, even if lower frequency waves are used to reduce the attenuation problem. For example, the test range achievable in a line with 1.0 dB/ft attenuation is less than about 10 feet for detection of 5-percent defects and 15 feet for detection of 20-percent defects [6]. Lowering guided-wave frequency (from 30 to 40 kHz to 10 to 20 kHz) to reduce the attenuation problem and thus to extend the test range, however, may not produce good test results because defect detection capability suffers due to the increased wavelength that occurs with decreasing wave frequency.

As mentioned in Section 2.1, pipeline operators consider the long-range guided-wave inspection technology a useful tool for ICDA and ECDA of unpiggable lines. To apply the guided-wave inspection technology to buried lines requires excavation of the line and removal of coating for guided-wave probe placement and, after the testing, recoating and site restoration. Therefore, applying the guided-wave inspection technology to examine a relatively short section of buried lines is an expensive process. Additionally, the cased section of a coated line at highway road crossings may be too long to examine using the guided-wave technology.

Therefore, to make the guided-wave inspection technology more useful and economical for DA applications, a need exists to improve its test range and inspection capabilities. The project described in this report is a part of the R&D effort expended to achieve the needed improvement.

3. HIGH-POWER MsS DEVELOPMENT

3.1 Technical Objective and Approaches

3.1.1 Technical Objective, Target Goal, and Test Range Extension

The technical objective of this project was to increase the guided-wave power of the magnetostrictive sensor (MsS) technology so that the test range of guided wave achievable on pipelines could be further extended. The target goal of the project was a 20-fold (or 26-dB) increase in the guided-wave signal amplitude over the level achievable at the beginning of the project.

The extension in the test range attainable by a 20-fold increase in the guided-wave signal amplitude depends on the wave attenuation coefficient, α, of the pipeline under testing and is equal to $26/(2\alpha)$, where the factor 2 accounts for the round trip. Figure 5 shows a table of attainable extension in test range with the 20-fold increase in signal amplitude.

Line Attenuation α (dB/ft)	Attainable Test Range Extension (ft)
2.0	6.5
1.0	13
0.5	26
0.25	52
0.1	130
0.05	260

Figure 5. Table of attainable extension in test range with a 20-fold increase in signal amplitude

3.1.2 Previous MsS Specifications and Technical Approaches for Enhancing Power

Previous MsS specifications used for T-mode piping inspection included the following:

(1) *Strip material*—Annealed nickel 201, 0.65 to 0.75 inch in width, 0.005 to 0.010 inch in thickness,

(2) *MsS coil*—16-conductor ribbon cable, and

(3) *Excitation voltage applied to MsS coil*—60 volts peak to peak.

The inspection capabilities achievable using 32-kHz T-mode included:

(1) *On straight aboveground bare/painted pipeline*—Typically over 100 feet in one direction for detection of 2- to 3-percent defects [2], and

(2) *On straight aboveground bitumen-coated pipeline (with approximately 0.3-dB/ft attenuation)*—Approximately 50 feet in one direction for detection of 20-percent defects [6].

The technical approaches for power enhancement that were evaluated and used in this project included:

(1) *Sensor optimization*—Optimize the width and thickness of the strip material, the number of MsS coil turns, and the excitation voltage.

(2) *Multiple sensor pairs*—Arrange multiple sensor pairs so that the signals generated or detected by each sensor pair are constructively added.

(3) *Better strip material*—Find and use a strip material that has better magnetostrictive properties than nickel.

3.2 Evaluation of Power Enhancing Approaches

3.2.1 Sensor Optimization

Figure 6 shows the dependence of the 16-, 32-, and 64-kHz T-mode signal amplitudes on the strip width relative to the wavelength. The data plotted in Figure 6 were obtained from a 6-5/8-inch-OD steel pipeline sample using 0.005-inch-thick annealed nickel 201 strips that were 0.75 and 1.0 inch in width. In the plot, the signal amplitude was normalized in reference to the signal amplitude at 64 kHz obtained using a 0.75-inch-wide strip. For general guidance, the dependence calculated using an MsS model recently developed at SwRI is also plotted

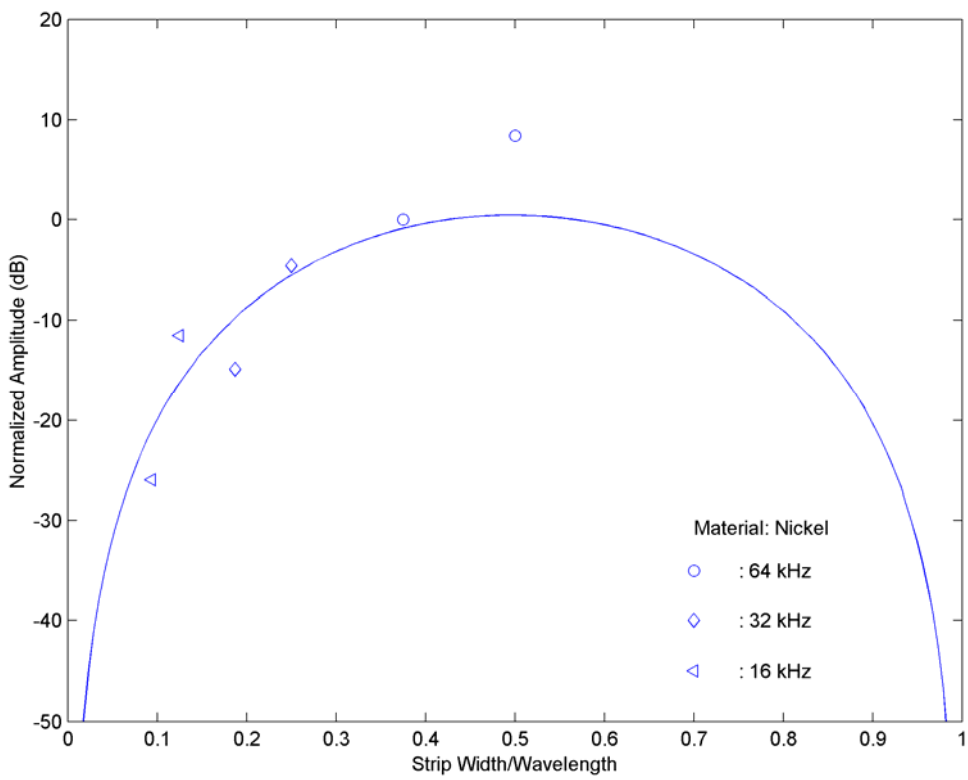

Figure 6. Dependence of signal amplitude on the strip width relative to wavelength

as a solid line in the figure [7]. The data showed that maximum amplitude would be obtained when the strip width is approximately one-half of the wavelength. For reference, the wavelength of torsional guided waves in steel pipe is approximately 2 inches at 64 kHz, 4 inches at 32 kHz, and 8 inches at 16 kHz.

As discussed in Section 2.3, two guided-wave probes placed side by side are used to control wave direction. Wave direction control requires that the spacing between the two probes be one-fourth of the wavelength. Consequently, the maximum strip width that can be used in practice is limited to one-fourth of the wavelength.

The data in Figure 6, together with the direction control requirement, indicate that the optimum strip width for MsS is one-fourth of the wavelength; namely, 1 inch for 32 kHz and 2 inches for 16 kHz. Compared to the previous practice of using 0.65- to 0.75-inch-wide strips at all frequencies, the optimization of the strip width to one-fourth of the wavelength would increase the signal amplitude by approximately 6 dB at 32 kHz and 16 dB at 16 kHz.

Figure 7 shows the dependence of signal amplitude on strip thickness. The solid lines are those calculated using the MsS model [7]. The other symbols (circles, diamonds, and triangles) are experimental data obtained using 0.005- and 0.010-inch-thick, 0.75-inch-wide, annealed nickel 201 strips. At a given frequency, the effects of thickness on signal amplitude were minor for thicknesses 0.005 inch or greater; for example, the amplitude is enhanced by only approximately 2 dB when strip thickness is increased from 0.005 to 0.010 inch. When the strip

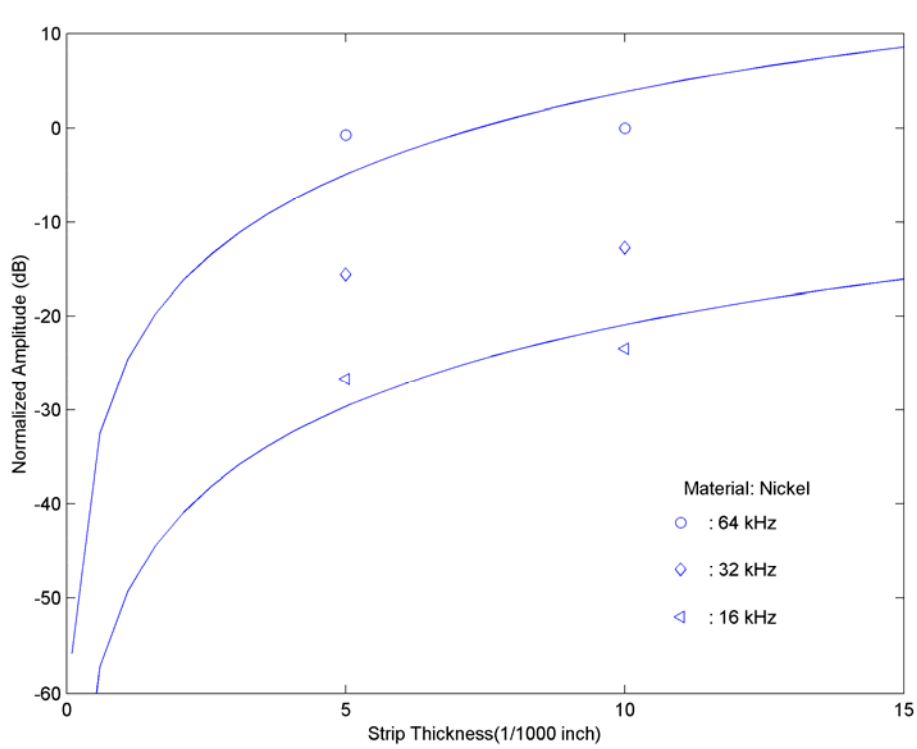

Figure 7. Dependence of signal amplitude on the strip thickness (material: nickel 201)

thickness is less than 0.005 inch, the signal amplitude decreases significantly with decreasing thickness; for example, by approximately 20 dB when the thickness decreased from 0.005 inch to 0.001 inch, per the results of a previous study [8]. Considering material cost, handling ease, and dependence of signal amplitude on strip thickness, the optimum strip thickness is from 0.005 to 0.010 inch.

Figure 8 shows the electric current that is supplied to a 16-turn MsS coil by the MsS instrument when the excitation voltage is set to 180 volts peak-to-peak. (Note: The instrument's maximum excitation voltage is 300 volts peak-to-peak.) Since the electrical impedance of the coil increases with the excitation frequency, *f*, and the diameter, *D*, of the coil (or the pipe under test), the electric current, *I*, decreases with both *f* and *D*. The empirical relationship between them was determined by fitting a curve through experimentally measured data points (represented with symbols shown in figure). The relationship was found to follow:

$$I = 364\, D^{-0.7}\, f^{0.8},$$

where *D* is in inches, *f* is in kHz, and *I* is in amperes.

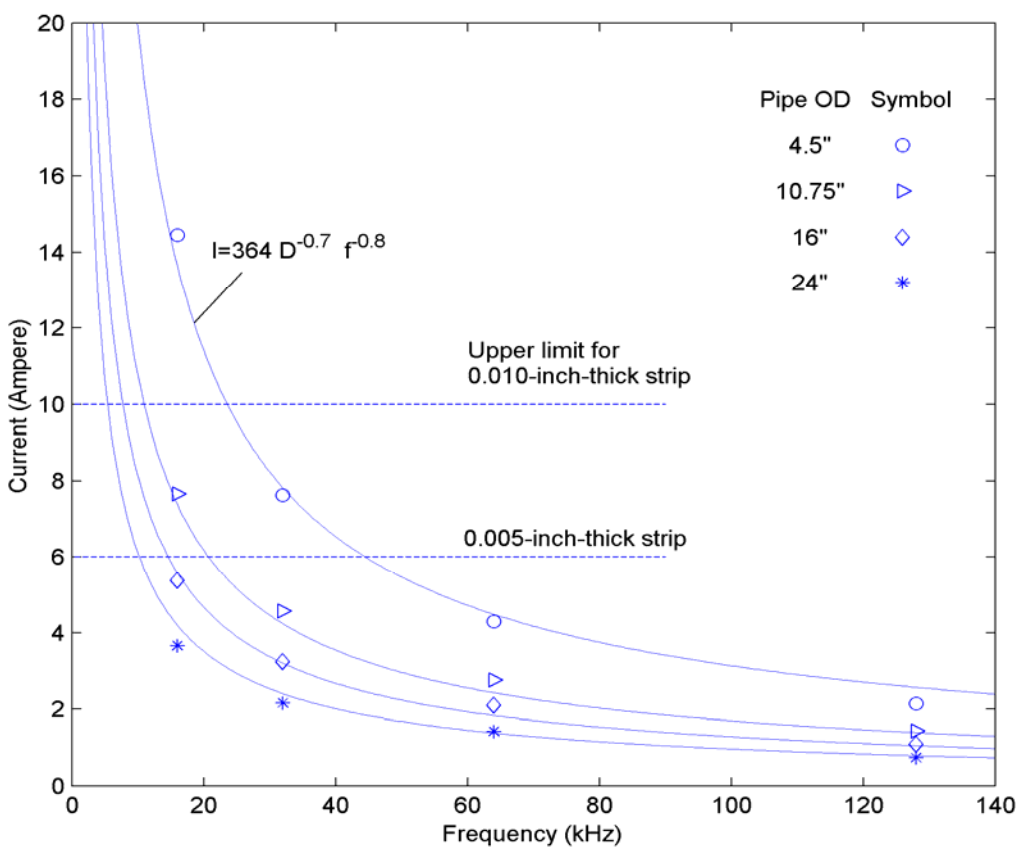

Figure 8. Relationship between the applied current in the MsS coil, excitation frequency, and coil diameter

The upper limit of excitation current level that can be applied to the MsS coil without causing degradation in sensor sensitivity (through demagnetization of the strip material) is also indicated in the figure. For both nickel and Hiperco® 50HS (details are given in Section 3.2.3), the upper limit was approximately 6 amperes for 0.005-inch-thick strips and 10 amperes for 0.010-inch-thick strips. In frequencies below 40 kHz, the use of 0.010-inch-thick strips instead of 0.005-inch-thick strips can improve the signal amplitude by a factor of 2 to 3 (or 6 to 10 dB)—this improvement is gained through a higher excitation.

Figure 9 shows how the signal amplitude changes with the increasing excitation voltage. The data were from a 16-inch-OD pipe, and the 100-percent MsS transmitter output corresponds to 300 volts peak-to-peak excitation voltage. At a given frequency, the peak current in the MsS coil and, thus, the peak AC magnetic field applied to the strip for guided-wave generation, is linearly proportional to the excitation voltage. Therefore, if the wave generation were linear to the applied AC magnetic field, the signal amplitude would increase by approximately 14 dB when the excitation is increased from 20- to 100-percent MsS transmitter output (a factor of 5 increase). All data in Figure 9 fall below the linear response line and show a nonlinear response. The nonlinear response means that the applied AC magnetic field has exceeded the linear response range and is approaching the level that causes a demagnetization of the strip material. The peak amplitude point at 60-percent MsS transmitter output for 16 kHz indicates that the applied AC magnetic field is at about the demagnetization level.

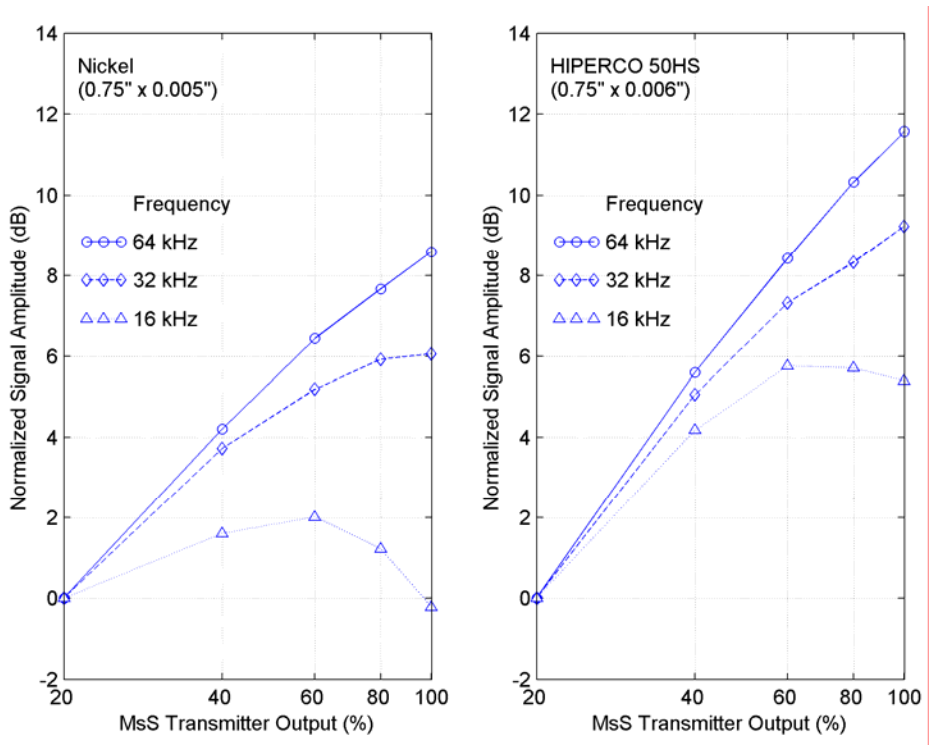

Figure 9. Signal amplitude versus the excitation voltage: 100-percent MsS transmitter output corresponds to 300 volts peak-to-peak excitation voltage. The data are from 16-inch-OD pipe.

The optimum sensor performance would be obtained by adjusting the excitation voltage of the MsS instrument and MsS coils so that the coils are operated at the upper limit of the excitation current level that can be applied without degrading sensor sensitivity. For reference, the existing MsS instrument is current-limited (to a maximum of 20 amperes) for low-impedance coils and is voltage-limited (to a maximum of 300 volts peak-to-peak) for high-impedance coils.

3.2.2 Multiple Sensor Pairs

Figure 10 shows 32-kHz T-mode signal amplitude data obtained from a 16-inch-OD pipe using different numbers of sensor pairs at various levels of excitation voltage. A total of three sensor pairs installed on the pipe for the measurements are shown in the photo in Figure 11. In the photo, sensors 1 and 2 comprised sensor pair 1, sensors 3 and 4 comprised sensor pair 2, and sensors 5 and 6 comprised sensor pair 3. The data obtained with a single sensor pair are indicated with open symbols in Figure 10—for example, open circles indicate those obtained with sensor pair 1, open diamonds indicate those obtained with sensor pair 2, etc. The data obtained with two sensor pairs connected in series are indicated with filled symbols—for example, filled circles indicate those obtained with sensor pairs 1 and 2, filled diamonds indicate those obtained with sensor pairs 2 and 3, etc. The data obtained with all three sensor pairs connected in series are indicated with * symbols. The variations in signal amplitude among the three single sensor pairs were small (approximately 1.5 dB). Compared to the single sensor pairs, two sensor pairs showed approximately 6.5 to 7.5 dB larger signal amplitudes, while three sensor pairs showed approximately 9.5 to 11.5 dB larger signal amplitudes.

Conservatively, the data in Figure 10 show that the signal amplitude increases in proportion to the number of sensor pairs—namely, two pairs increase it by a factor of 2 (6 dB), three pairs by a factor of 3 (9.5 dB), and so forth.

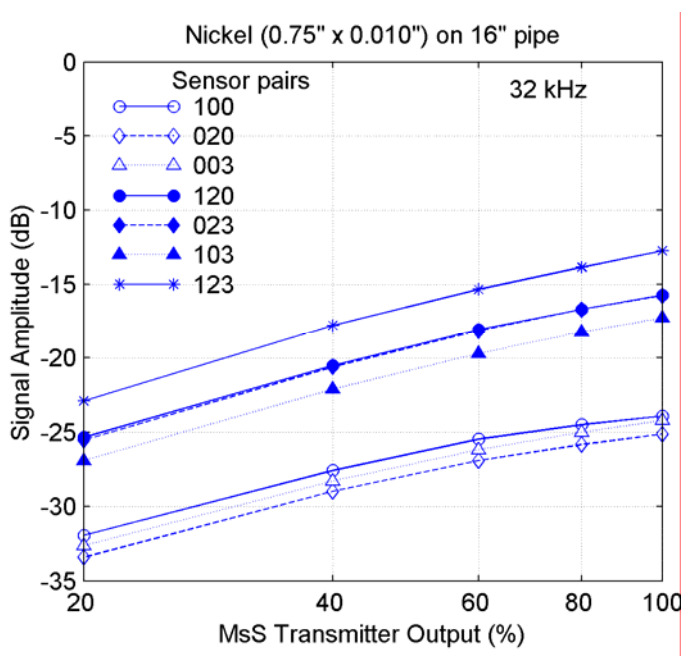

Figure 10. Signal amplitude obtained using different numbers of sensor pairs

Figure 11. Photo of three pairs of strips installed on a 16-inch-OD pipeline sample (strips are hidden below the duct tape)

3.2.3 Better Strip Materials

For MsS applications, materials with higher magnetostriction coefficients would yield higher signal amplitude. Giant magnetostrictive materials, such as Terfenol®, would be ideal, but they are brittle and are not produced in a strip form. Iron-cobalt alloys are produced in strip forms and are known to have higher magnetostriction coefficients than nickel [9].

In this project, an iron-cobalt alloy, Hiperco 50HS, produced by Carpenter Technology, was evaluated as an alternate strip material to annealed nickel 201. Physical properties of Hiperco 50HS and annealed nickel 201 are tabulated in Figure 12. Hiperco 50HS requires a specific heat-treatment to exhibit the physical properties listed in the table.

	Hiperco 50HS	Nickel 201
Chemical Composition (%)	49 Fe, 49 Co, 1.9 V, 0.05 Mg, 0.05 Si, 0.01 C, 0.3 Cb/Nb	99 Ni, 0.25 Cu, 0.4 Fe, 0.35 Mg, 0.02 C, 0.35 Si, 0.01 S
Saturation Magnetostriction	60×10^{-6}	35×10^{-6}
Curie Temperature	1720°F (938°C)	662°F (350°C)
Magnetic Saturation	24,000 gauss	6,100 gauss
Yield Strength	73 ksi	15 ksi
Density	8.1 g/cm^3 (0.293 lb/in^3)	8.9 g/cm^3 (0.322 lb/in^3)

Figure 12. Physical properties of Hiperco 50HS and annealed nickel 201

Figure 13 shows the experimental data obtained at 64, 32, and 16 kHz from 6-5/8-inch-OD and 16-inch-OD pipeline samples using 0.75-inch × 0.006-inch Hiperco 50HS strips, compared to those obtained using 0.75-inch × 0.005-inch annealed nickel 201 strips. The excitation voltage was kept the same for the experimental measurements. As shown, the Hiperco 50HS strip was better than the nickel 201 by approximately 12 dB on 16-inch-OD pipe and 18 dB on 6-5/8-inch-OD pipe.

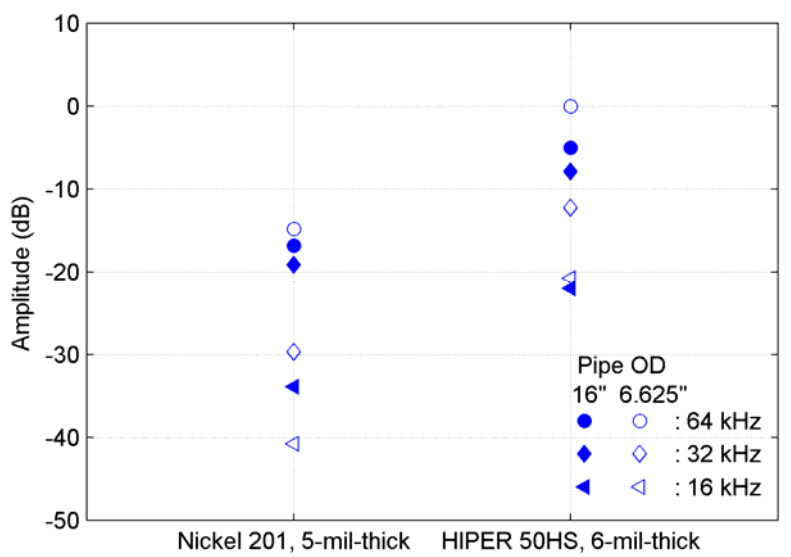

Figure 13. Comparison of signal amplitudes obtained using Hiperco 50HS and annealed nickel 201 strips

From the above results and ignoring the slight thickness difference, it was concluded that the Hiperco 50HS strip material is approximately 4 times (12 dB) better than the annealed nickel 201 strip material.

Because the Hiperco 50HS has a high mechanical strength and the strip materials are delivered in small radius (approximately 2-inch) rolls, 0.010-inch-thick strips were found too stiff for use. Consequently, 0.006-inch-thick strips have been in use.

Some iron-cobalt alloys (for example, 30% Fe/70% Co) exhibit saturation magnetostriction that is as high as 130×10^{-6} [9]. These alloys can be produced in strip forms but, due to the lack of commercial demand, are not presently available for use. Based on the improvement gained with the Hiperco 50HS, it is believed that these alloys could provide an additional 12-dB (factor of 4) increase in signal amplitude.

3.2.4 Summary

From the evaluation results of the power-enhancing approaches described in Sections 3.2.1 through 3.2.3, the magnitude of signal amplitude increase that can be achieved for practical use can be summarized as follows:

(i)	Hiperco 50HS	12 dB
(ii)	Strip width matched to 0.25 wavelength	6 dB min
(iii)	Three sensor pairs	9.5 dB
(iv)	Higher excitation (a factor of 2 or more)	6 dB min
Total		33.5 dB

The above total (33.5 dB) is equivalent to an approximately 50-fold increase in the signal amplitude over the previously obtained signal level. The 6-dB minimum gain with higher excitation does not apply to small-diameter (4 inches or less) pipes. On small-diameter pipes, the total gain obtainable is 27.5 dB (an approximately 24-fold increase). The above increase in signal amplitude applies to the 32-kHz or lower frequencies typically used for long-range piping inspection.

The target goal of 20-fold increase in the signal amplitude is thus achievable using a combination of the four approaches listed above.

3.3 Other Improvements

3.3.1 Time-Controlled Gain

A manual time-controlled-gain (TCG) function was added to the MsS instrument so that the effects of wave attenuation on the detected signals could be compensated. The overall gain that can be controlled by this new feature is 80 dB. Figure 14 shows 32-kHz T-mode data acquired from an aboveground 125.5-foot-long, 6-5/8-inch-OD, bitumen-coated pipeline sample with the TCG off (top) and on (bottom). The wave attenuation in the above bitumen-coated pipeline sample was approximately 0.25 dB/ft at 32 kHz. As shown when acquired with TCG and, thus, the effects of wave attenuation compensated, the quality of the data became much better and the interpretation of the data much easier.

The data in Figure 14 were obtained by using 0.75-inch × 0.006-inch Hiperco 50HS strips and three sensor pairs—namely, the power-enhancing approaches (i) and (iii) in Section 3.2.4. The signal at 104 feet in Figure 4 was caused by the end-reflected signal that was reflected back by the 20-percent defect at approximately 62 feet and rereflected from the end. This multiple-reflected 20-percent defect signal was clearly detectable with the signal-to-noise ratio (SNR) of approximately 4 (12 dB), indicating that the test range of the improved MsS on bitumen-coated lines in air exceeded 100 feet. Previously, the achievable test range for detecting 20-percent defects on a bitumen-coated pipeline in air was approximately 50 feet at 32 kHz [6]. The extended test range achieved in this example is consistent with the expected amount tabulated in Figure 5 and is evidence that the target goal of increasing the signal amplitude by 20-fold has been achieved.

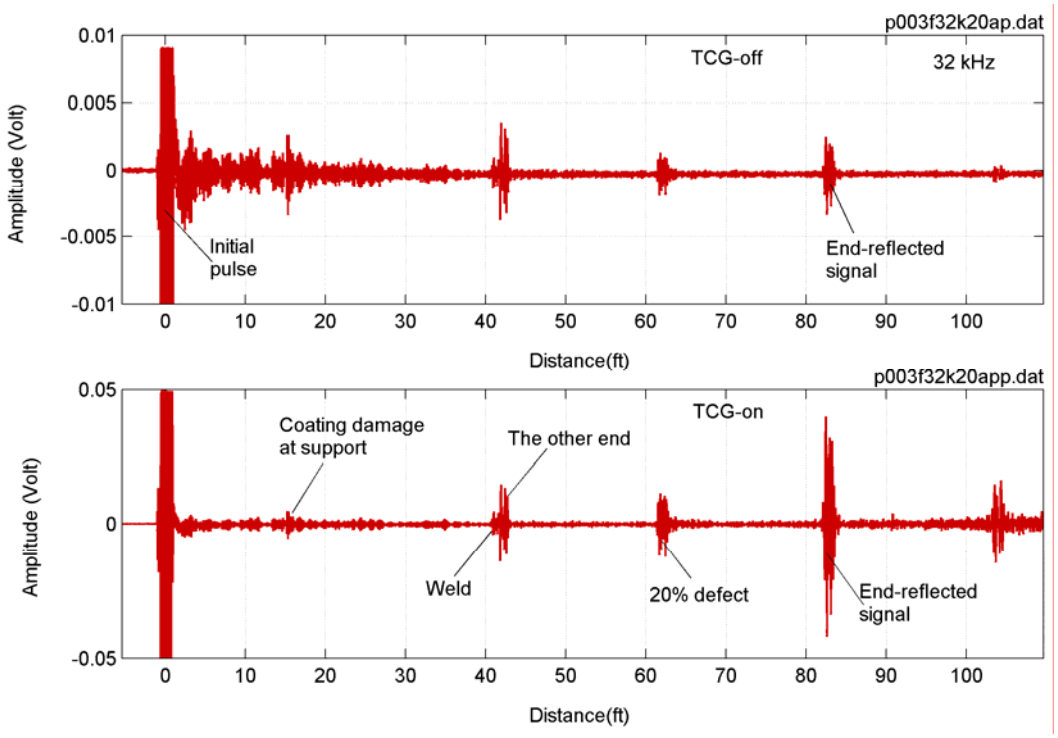

Figure 14. Comparison of data acquired from an aboveground 125.5-foot-long, 6-5/8-inch-OD, bitumen-coated pipeline sample with (bottom) and without (top) TCG

3.3.2 Calibration

A calibration procedure using a hose clamp was introduced. The procedure involves placing a hose clamp tightly around a pipe under testing at a location outside the dead zone of the MsS, detecting the signal reflected from the clamp, and calibrating all other detected signals in reference to the clamp signal. This procedure was found to be significantly better than the previous practice of using weld signals as reference. Since weld signals vary widely from weld to weld and from pipe to pipe, they do not provide a good and consistent calibration.

Figure 15 shows a picture of the hose clamp placed on a 20-inch-OD pipeline for calibration purposes. The hose clamp used in this project was an off-the-shelf commercial item made of 9/16-inch-wide, 0.022-inch-thick stainless steel band.

In order to calibrate other detected signals using the hose-clamp signal, the reflection coefficient of the hose clamp on a pipe under testing must be known beforehand. This requires a preestablished table of reflection coefficients of hose clamps on varieties of pipe diameters and wall thicknesses.

Figure 16 shows a plot of reflection coefficients of 9/16-inch-wide, 0.022-inch-thick hose clamps that were experimentally measured at 32 kHz (circles) and 16 kHz (diamonds) on different pipe sizes. The X-axis of the plot is normalized to the circumferential cross-sectional area of the hose clamp on a pipe relative to that of the pipewall (which is approximately equal to the hose-clamp thickness relative to the pipewall thickness). To guide the experimental data, calculated values per the transmission line model developed at SwRI [10] are also given in straight lines.

Figure 15. A hose clamp placed around a 20-inch-OD line for calibration purposes

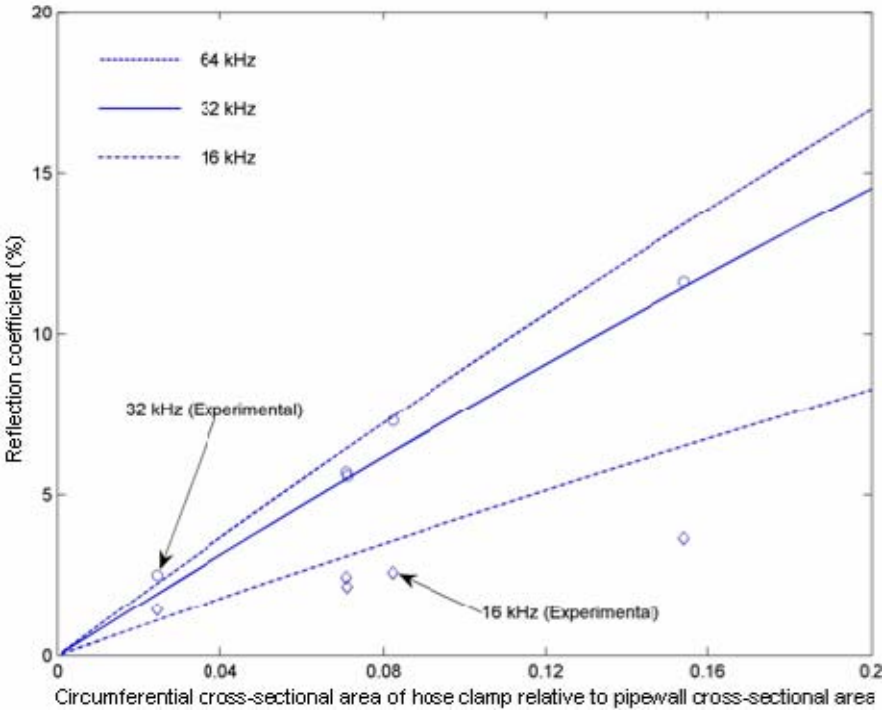

Figure 16. Reflection coefficients of hose clamp placed on various pipe sizes

The data in Figure 16 show that the reflection coefficient of hose clamp on a given pipe size varies with the wave frequency. The wave reflected from hose clamp is composed of two components that are added together—one reflected from the front edge of the clamp band and the other reflected from the rear edge of the clamp band in reference to the direction of wave propagation. The relative phase of the two components varies with wave frequency that leads to variations of the reflection coefficient with the wave frequency [11].

Considering the importance of the calibration in data interpretation, further refinement of the hose clamp calibration procedure and expansion of the reflection coefficient data are recommended.

3.3.3 Dry-Coupling Method

A dry-coupling method for generating and detecting T-mode guided waves using the MsS was introduced. This method would remove the need for adhesively bonding the strips around a pipe. The method involves placing the ferromagnetic strips around the pipe under test, placing MsS ribbon coils around the strips, and then pressing the strips with a bladder so that the T-modes generated in the strip would be mechanically coupled into the pipewall.

Figure 17 is a photo of the test arrangement set up on a 12-inch-OD pipe sample in laboratory for the dry-coupling method. The bladder was inflated with air and kept in place by a belt placed over it. The data obtained from the test sample are shown in Figure 18. The quality of data obtained was similar to that obtained with adhesively bonded strips. The bladder pressure required to obtain good quality data was approximately 30 to 40 psi (similar to pressures used for automotive tires).

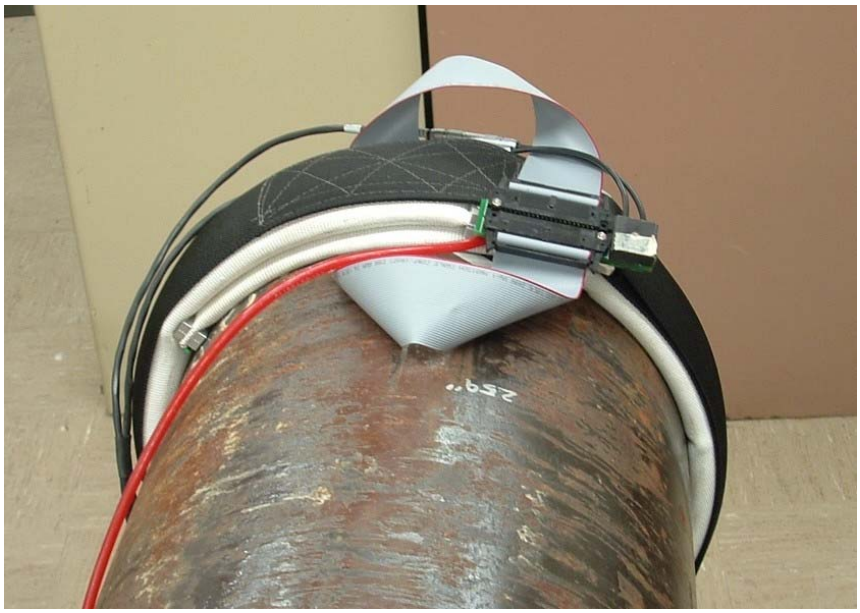

Figure 17. Photo of the dry-coupling arrangement for pipeline testing

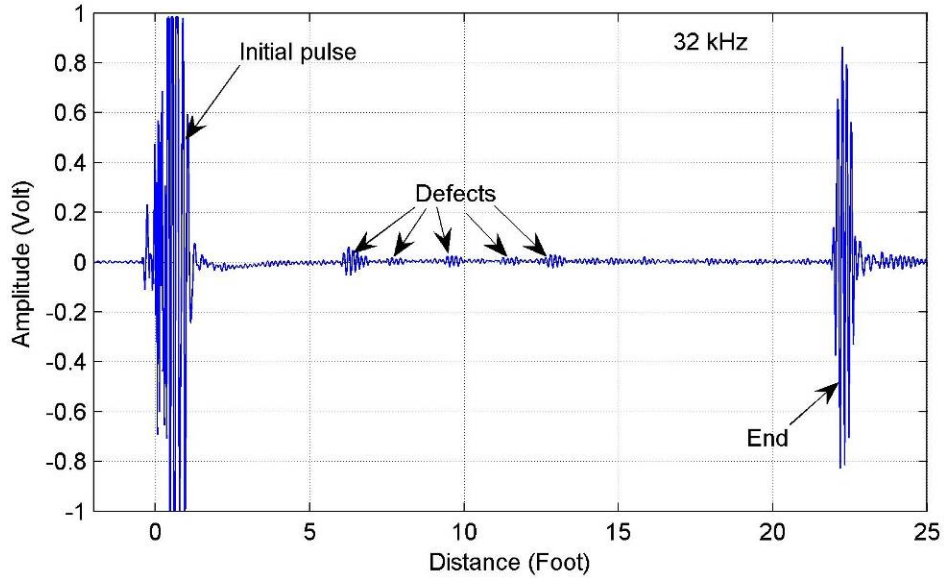

Figure 18. 32-kHz T-mode data obtained from a 12-inch-OD pipe using the dry-coupling method

Testing of the dry-coupling arrangement shown in Figure 17 on different pipe sizes has shown that it is usable on pipes of 12 inches or less OD. On larger size pipes, the bladder exhibits a tendency to slowly walk out of the belt; thus, the arrangement could not be used reliably. Refinement of the arrangement is being pursued to remove this instability problem.

3.3.4 Discrimination Between Weld and Defect Signals

A method for discriminating weld signals from defect signals was introduced. The method relies on the fact that the phase of a reflected wave from a discontinuity is opposite, depending on whether the incident wave sees more metallic cross-sectional area (such as at a weld) or less metallic cross-sectional area (such as at a defect). To further illustrate the point, 128-kHz T-mode data acquired from a pipe with a step-wise change in wall thickness are shown in Figure 19 [12]. When the incident wave moves up the step (upper plot), the reflected signal is in phase with the incident wave. When the incident wave moves down the step (lower plot), the reflected signal is in opposite phase to the incident wave.

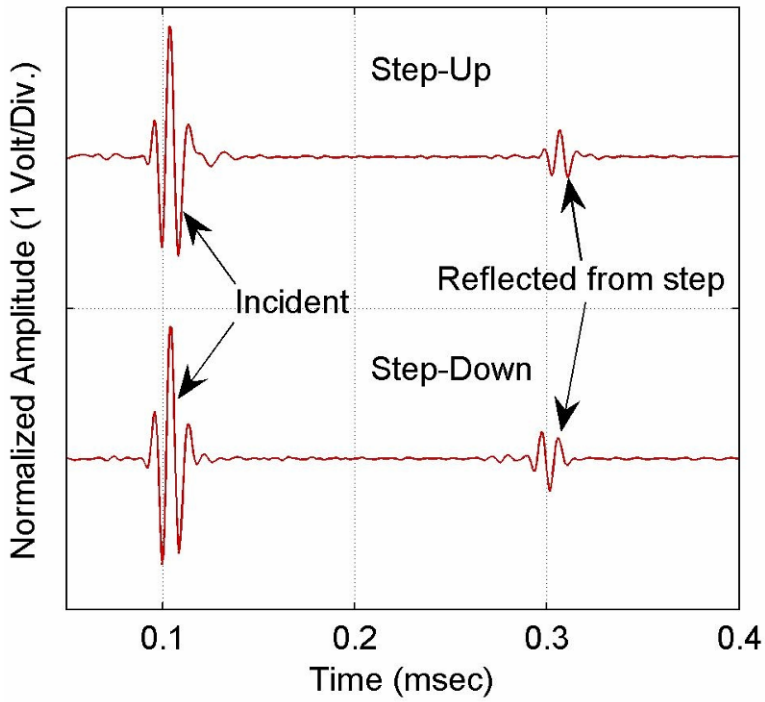

Figure 19. Incident and reflected signals from a step-wise change in pipewall thickness

4. FIELD TEST RESULTS AND FINDINGS

4.1 General

During the course of the development in this project, the performance of the improved MsS was evaluated in the field. The evaluations were conducted at Battelle's Pipeline Simulation Facility (PSF) in Columbus, Ohio; Southern California Gas Company's lines in Goleta, Valentia, and Los Angeles, California; Gulf South Pipeline Company's lines in Vicksburg, Mississippi, and Tyler, Texas; and Con Edison Company's Astoria, Queens Facility in New York City.

General overall findings obtained from the field tests are described in the following subsections.

4.2 Inspection Capabilities on Aboveground Straight Pipelines

To show the extent of inspection capabilities achievable with the high-power MsS on aboveground straight pipelines, an example of the MsS data obtained from the field evaluations is given in Figure 20. The data were obtained from a 16-inch-OD, 1.039-inch-wall gas transmission line shown in Figure 21 using a 32-kHz T-mode. The pipeline (the left one in the photo) was painted and was sitting on rollers at support places along the line. One pair of MsS probes, utilizing 1.0-inch × 0.006-inch Hiperco 50HS strips, was placed around the pipe at a location near the van. At the far end of the straight section of the line in the photo, the line had a flange connection. The distance to the flange was about 500 feet from the MsS pair, and there were a total of 19 girth welds (including the weld for the flange) between the sensor and the flange. Among the four power-enhancing approaches listed in Section 3.2.4, three (i, ii, and iv) were used to acquire the data in Figure 20. The expected increase in signal amplitude was approximately 24 dB (a factor of approximately 16). As shown, all 19 welds were clearly detectable with good SNR.

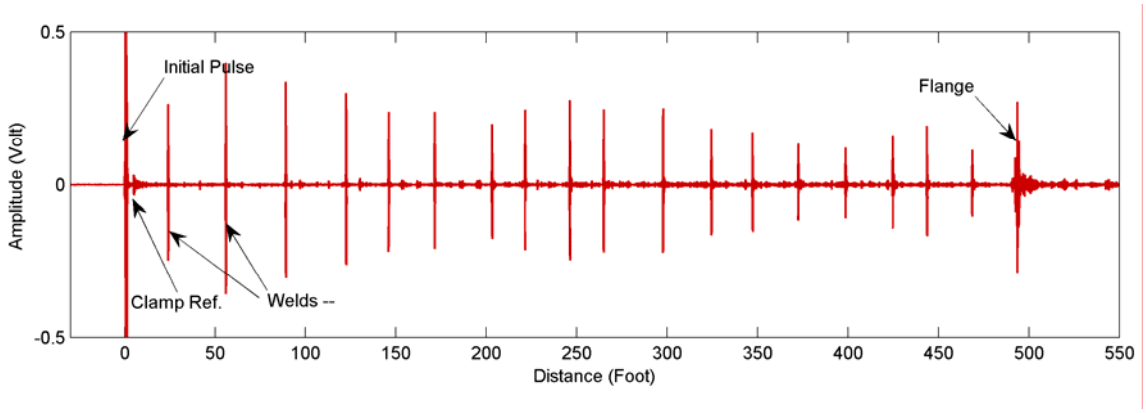

Figure 20. 32-kHz T-mode data obtained from a 16-inch OD aboveground straight pipeline

Figure 21. A photo of 16-inch OD gas transmission line and MsS test setup

Figure 22 shows processed video data of the acquired rf (radio frequency) data in Figure 20. The data process involved conversion of rf data to video data, wave attenuation correction (so that on average the weld signals would be approximately constant; they vary in amplitude because they were not made the same), and calibration in reference to the hose-clamp signal (which corresponded to an approximately 1.5-percent reflection on this pipeline). To show the noise level variation over the entire distance, the expanded view of the data in Y-axis is given in the middle of Figure 22. Many small signals seen in the data were caused by rollers at supports and by multiple reflections between welds. Also to show the quality of data, an expanded view of the data near the flange is given at the bottom. Signals from a couplet (a 2-inch-OD branch pipe for a gauge) and the flange weld were readily resolved from the large flange signal in the expanded view.

The data in Figures 20 and 22 indicate that the test range achievable in aboveground straight pipelines using the high-power MsS is over 500 feet in one direction for detection of 2-percent defects. Considering the excellent SNR in the expanded view near the flange at 500 feet, the inspection range achievable in straight lines with no stoppers such as flanges could be 1000 feet in one direction.

Figure 23 shows another example of processed 32-kHz T-mode data that were acquired from a cased 10-3/4-inch-OD, 0.843-inch-wall, gas transmission pipeline at road crossings. A photo of the line (left one) is shown in Figure 24. The line traversed a highway (far side in the photo) and a road (near side in the photo) and had a 15-degree miter joint (at the bent area in the photo). The line was painted, and the length of the cased section was approximately 253 feet

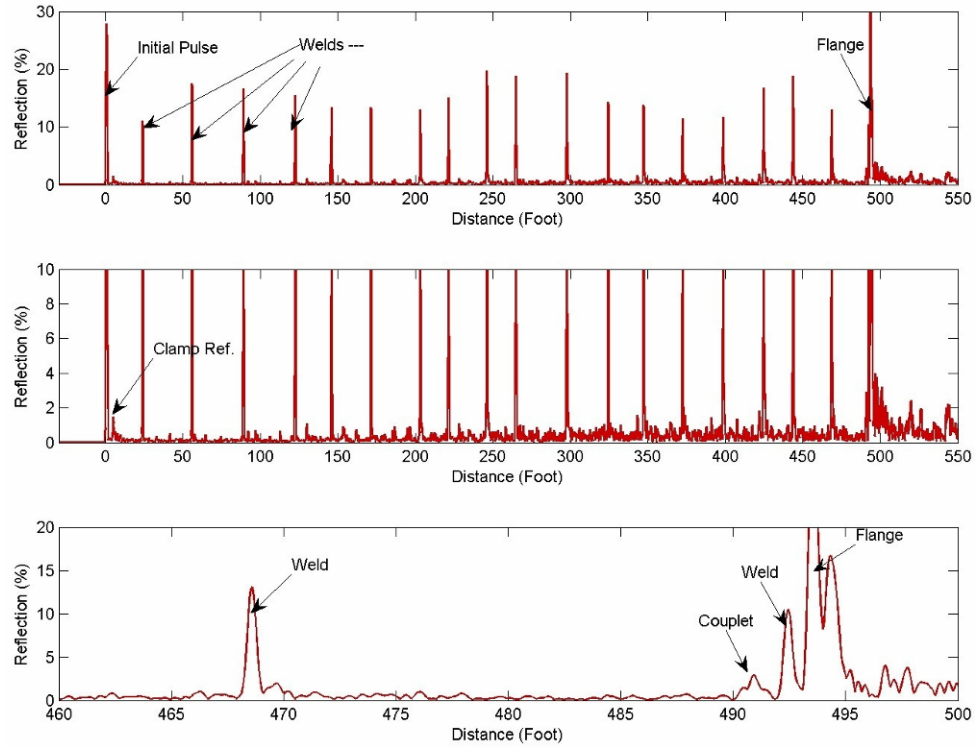

Figure 22. Processed data of the 32-kHz T-mode data in Figure 19

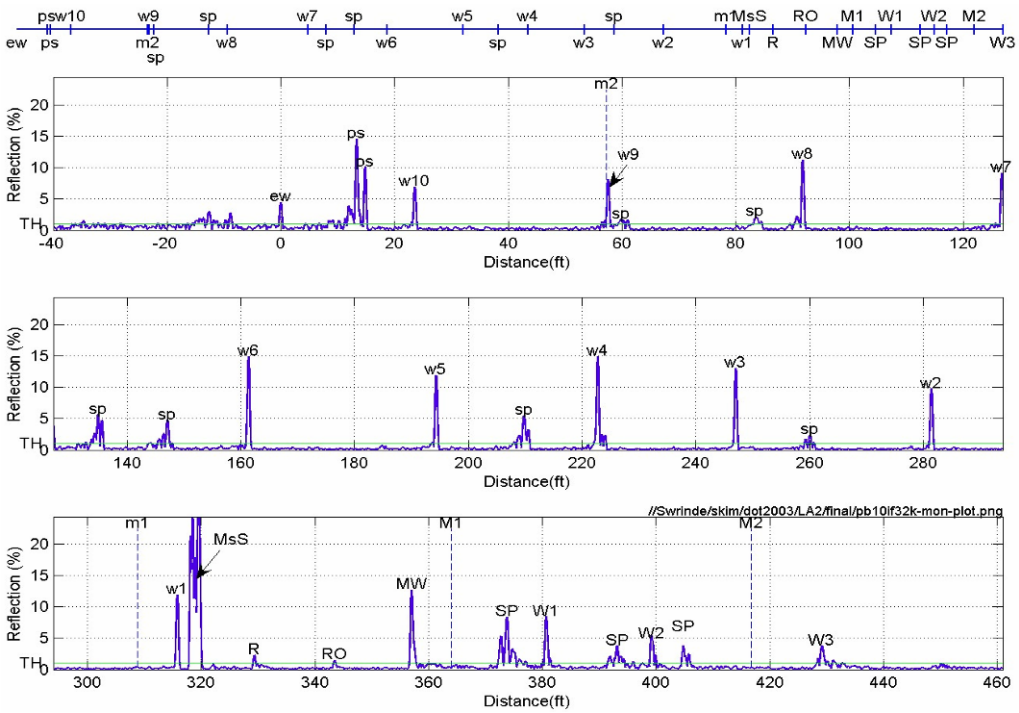

Figure 23. 32-kHz T-mode data from a 10-3/4-inch cased line. MsS location at about 320 feet; m1, m2 – highway casing ends; M1, M2 – road casing ends; w, W – welds; sp, SP – spacers; ps – pipe support; R – clamp reference (equivalent to 2-percent defect in this case); RO – roller; MW – miter weld

Figure 24. Photo of 10-3/4-OD cased pipeline (left) at road crossings

under the highway and 53 feet under the road. In the cased section, spacers such as those shown in Figure 25 were clamped on the line at intervals. The cased section of the line under the road was partially buried with soil carried into the casing by flooding water. The data in Figure 23 were taken with one MsS pair placed approximately 10 feet from the highway-casing end in the photo, again utilizing the power-enhancing approaches i, ii, and iv.

The distance in the Figure 23 plot was referenced to the weld of a short radius elbow across the highway. Thus, in the plot, the MsS was located at approximately 320 feet. The highway casing ends (indicated as m1 and m2) were at approximately 57 to 310 feet. The casing ends of the road (indicated as M1 and M2) were at 363 and 417 feet. On this pipeline, the clamp reference signal (R at 330 feet), used for calibration, corresponded to an approximately 2-percent defect. The spacers clamped on the cased section of the line produced a characteristic signal pattern and, thus, their signals were readily distinguishable from weld signals.

As shown, a section of the cased line more than 250 feet long under the highway could be inspected from one side of the highway for detection of 2-percent defects. The test range on the highway cased section was limited to somewhat over 300 feet in this case, due to the presence of the short radius elbow at 0 feet. The test range on the road cased section was limited to approximately 100 feet, primarily due to the increased wave attenuation caused by the soil.

Figure 25. Photo of a spacer used on the cased section of pipelines

4.3 Inspection Capabilities on Buried Pipelines

Figure 26 shows an example of 32-kHz T-mode data acquired from a buried flow-loop pipeline at Battelle's Pipeline Simulation Facility (PSF) in Columbus, Ohio. The line was constructed of 24-inch-OD, 0.344-inch-wall, electric-resistance-welded (ERW) pipes with fusion-bonded-epoxy (FBE) coating. The line contained various machined-in defects for validation of pipeline pigging inspection tools (further detailed information on the flow loop can be obtained from http://www.battelle.org/pipetechnology/FLOWLOOP/ MAIN.HTML).

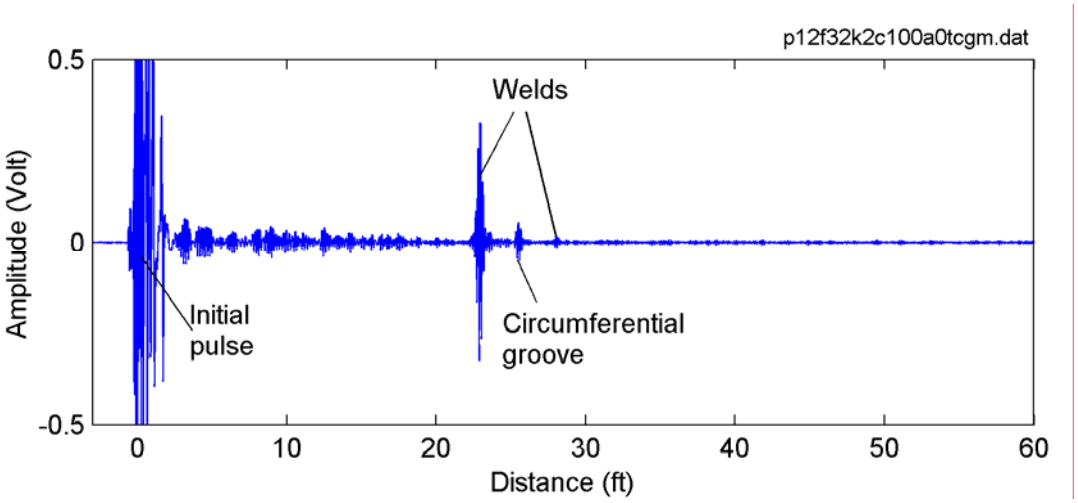

Figure 26. 32-kHz data from a 24-inch-OD buried pipeline with a fusion-bonded-epoxy coating

The data in Figure 26 were obtained from an excavated hole approximately 25 feet from the location of a 20-percent-deep circumferential groove; one of the reference defects placed on the flow loop. When the flow loop was constructed, the circumferential groove was machined at the mid-length point of a 5-foot-long pipe sample that was subsequently welded into the flow loop. The data in Figure 26 were taken using two MsS pairs with 0.75-inch × 0.006-inch Hiperco 50HS strips and higher excitation with the expected signal amplitude increase of approximately 24 dB (a factor of approximately16). A photo of the test setup on the 24-inch-OD flow loop in an excavated hole is shown in Figure 27.

Figure 27. Test setup on the 24-inch-OD flow loop at PSF

The data in Figure 26 showed the signals from the 20-percent circumferential groove and the two adjacent welds separated by 5 feet. Beyond the second weld signal, there were no detectable signals, indicating that, even with the improved MsS, the achievable test range on buried lines is severely limited because of high wave attenuation. The impact of high attenuation can be seen from the huge difference between the first and second weld signal amplitudes in Figure 26. If the pipeline was not buried and the welds were made similarly, the two weld signals would have approximately the same amplitude. Based on the decrease in the weld signal amplitudes, the attenuation on this buried section of the flow loop was estimated to be approximately 2.5 dB/ft, which is significantly higher than the anticipated attenuation of around 1.0 dB/ft [6].

Data obtained using 16-kHz T-mode were inferior to the 32-kHz data, suggesting that lowering the wave frequency may not improve inspection capabilities on buried lines.

Figure 28 shows another example of data obtained from buried pipelines. The line was a bitumen-coated, 22-inch-OD, 0.281-inch-wall, gas transmission pipeline. The data were taken from four different excavation holes, using both 16- and 32-kHz T-modes. For 32-kHz testing, two pairs of sensors, utilizing 1.0-inch × 0.006-inch Hiperco 50HS strips and higher excitation, with the expected signal amplitude increase of approximately 30 dB (factor of approximately 30), were used. The strips for 32 kHz were also used for 16-kHz testing with a single sensor pair, with the expected signal amplitude increase of approximately 24 dB (factor of approximately16). A photo of MsS set up in one of the excavated holes is shown in Figure 29.

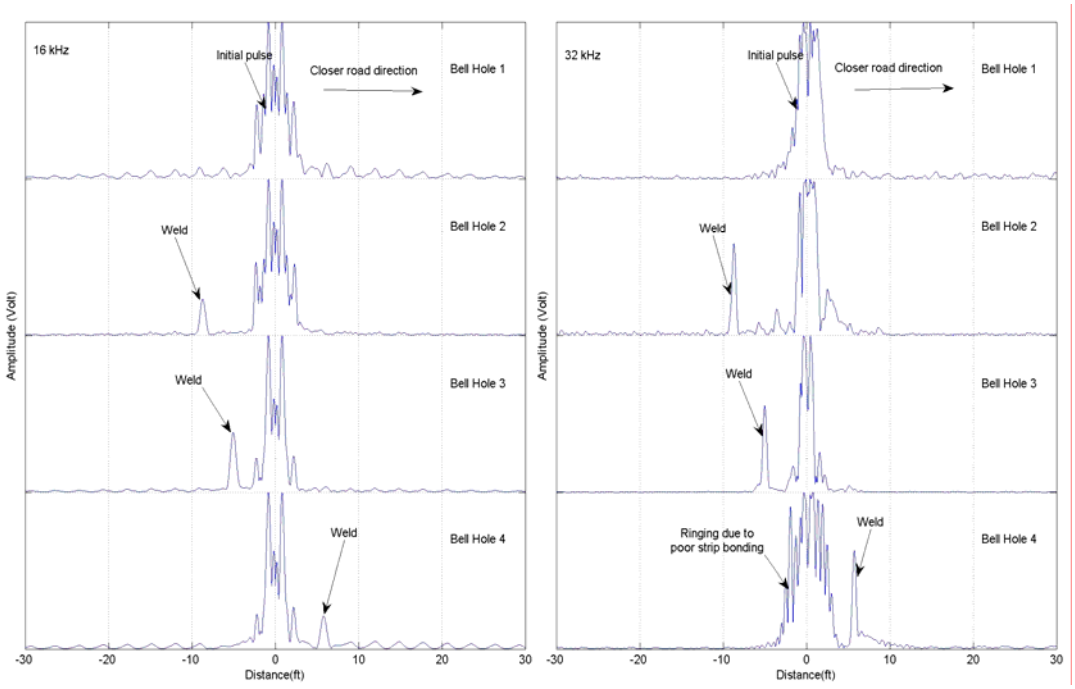

Figure 28. 16- and 32-kHz data acquired from a buried, bitumen-coated, 22-inch-OD pipeline

Figure 29. MsS setup on a 22-inch bitumen-coated pipeline in a bell hole

The data in Figure 28 show that welds located within 10 feet from the MsS probe were detectable. Except for the signal from the nearest weld, there were no other significant signals. Also, lowering the test frequency from 32 to 16 kHz did not improve the test range and SNR. The data from bell hole 1 (top plot in Figure 28) showed no weld signals. Since the pipeline was known to be made of 40-foot pipe joints, the absence of weld signals in this case meant one of the following: (1) the weld was located within the dead zone (about 2 feet) and was thus not detectable; 2) the MsS location is at about the mid-point of the pipe joint, and the welds at about 20 feet were not detectable because of high wave attenuation. If the weld is assumed to be 20 feet from the MsS and its reflection coefficient is similar to those of other welds detected from other bell holes, the attenuation in the line is calculated to be over 1.8 dB/ft at 32 kHz. Typically, the weld signal is equivalent to a 10- to 15-percent reflection at 32 kHz. It may be concluded, therefore, that the test range for detecting 10- to 15-percent defects in this pipeline is less than 20 feet.

Test results from other buried pipelines were similar to those described above. It was concluded, therefore, that because of high wave attenuation, the test range achievable on buried pipelines using the high-power MsS is limited to no more than 20 to 30 feet in one direction for detection of 20-percent defects.

4.4 Other Factors That Limit Inspection Capabilities

As described in Section 4.3, the condition of a buried pipeline can severely limit the inspection capabilities of the guided-wave technology. The actual magnitude of the effect, of course, varies with the soil type and compactness, moisture content in soil, depth of soil cover, coating type, and whether the line is directly surrounded by soil or cased (sleeved).

In addition to the buried pipeline's condition, achievable inspection range varies significantly depending on the construction features of the line. The effects of some of the line features on the inspection range are as follows.

- *Spacer* (Figure 25)—small
- *Small angle miter joint*—moderate
- *Roller* [Figures 30(a) and (e)]—negligible
- *Pipe support sleeve* [Figure 30(b)]—small to moderate (effects similar to large girth welds)
- *Clamp with fiberglass jacket* [Figures 30(c) and (d)]—moderate to high
- *Short radius elbow*—high
- *Branch piping* [Figure 30(f)]—small to high in proportion to branch pipe size relative to the main pipe size
- *Flange*—delimits the test range
- *Weld*—small to moderate; poorly welded joints can delimit the test range, as shown in Figure 31 data
- *Coating*—negligible (for thin fusion-bonded-epoxy coating) to high (for bitumen and polyethylene coating)

4.5 Summary

(1) In straight aboveground pipelines, the test range of the high-power MsS is more than 500 feet in one direction for detection of 2-percent defects.

(2) In buried pipelines where wave attenuation is high, the test range of the high-power MsS is no more than 20 to 30 feet in one direction for detection of 20-percent defects.

(3) The actual test range achievable on a pipeline depends on the specific conditions and features of the line under testing and would fall between the two ranges achievable on straight aboveground pipelines and on buried pipelines, respectively.

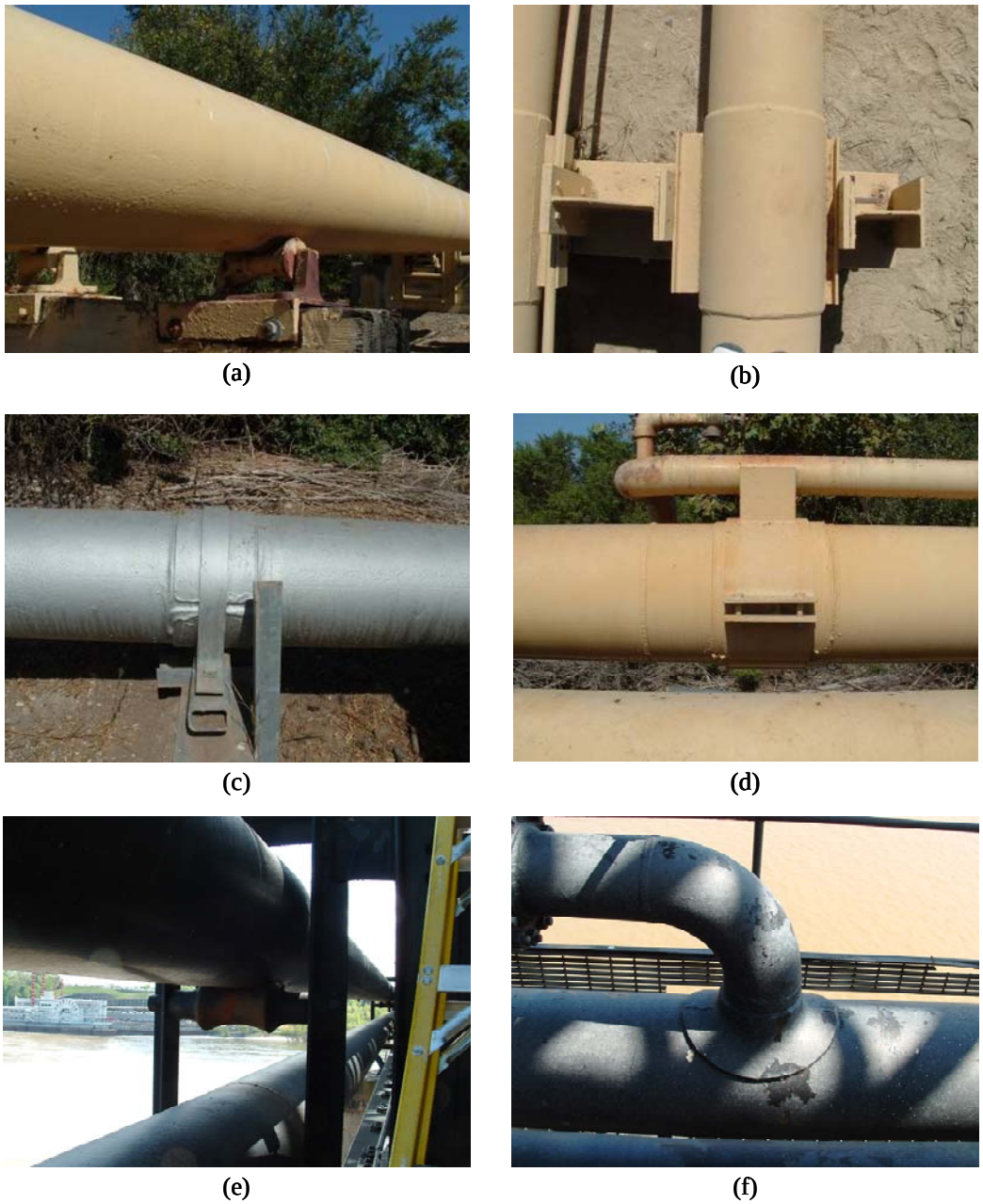

Figure 30. Photos of various line features: (a) and (e) roller; (b) pipe support sleeve; (c) and (d) clamp with fiberglass jacket; (f) branch piping

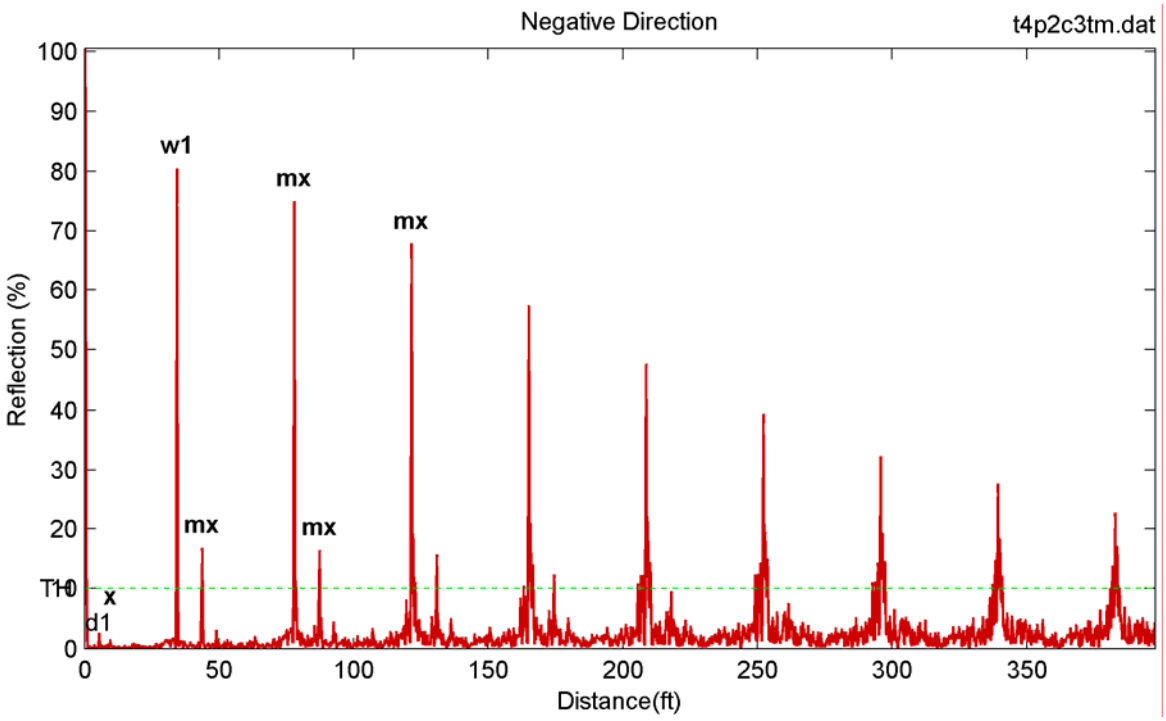

Figure 31. 32-kHz T-mode data obtained from a 14-inch-OD straight aboveground pipeline built in the early 1940s. The guided waves were reflected mostly from both ends of a 40-foot pipe joint and reverberated in the pipe joint. Poor welded joints at both ends were believed to be the cause.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

(1) The target goal of a 20-fold increase in signal amplitude was achieved by the combined use of better strip material (Hiperco 50HS), optimized strip width (to one-fourth of wavelength), higher excitation voltage, and multiple sensor pairs.

(2) In straight aboveground pipelines, the test range achievable with the high-power MsS was over 500 feet in one direction for detection of 2-percent defects.

(3) In buried pipelines, where wave attenuation is high, the test range of the high-power MsS is no more than 20 to 30 feet in one direction for detection of 20-percent defects.

(4) The actual test range achievable on a pipeline depends on the specific conditions and features of the line under testing and would fall between the two ranges achievable on straight aboveground pipelines and buried pipelines, respectively.

(5) Because of the severe effects of high wave attenuation, significantly extending the test range on buried lines seems impractical. For example, to extend the test range by an additional 20 to 30 feet on a buried line with 2-dB/ft attenuation would require 2 (round trip) $\times$ 2 dB/ft $\times$ 20 to 30 feet = 80 to 120 dB (or a factor of 10^4 to 10^6) additional increase in signal amplitude. The required improvement is beyond reach at the present time.

(6) Considering the high cost of excavation and the limited test range achievable, the routine usage of guided-wave inspection technology for a one-time survey of buried pipelines (unless the pipeline is excavated for some other reason) appears cost-ineffective.

(7) The pipelines for which the long-range guided-wave inspection technology is best used for ECDA and ICDA applications are lines that are difficult to access for direct examination and have low to moderate wave attenuation to allow long-range inspection. These pipelines include cased lines at road crossings, suspended lines across a river or valley, and insulated lines.

5.2 Recommendations

The long-range guided-wave inspection technology is a tool that can survey a large area of a structure and find defect locations quickly. When defect indications are found, their locations are examined in detail in a follow-up inspection using conventional techniques (such as ultrasonic testing) to obtain the defect characteristics (such as depth, width, and length) that are needed for assessing structural integrity and determining appropriate corrective measures. The above practice is necessary because of the present inability of the guided-wave technology to provide defect specifics. On pipelines that are difficult to access (such as cased-lines at road crossings), the follow-up inspection would be very costly and disruptive and, therefore, would not be conducted unless determined absolutely necessary. On such pipelines, maintenance decisions need to be made based on the guided-wave test results.

To facilitate the use of the long-range guided-wave inspection technology for ECDA and ICDA of difficult-to-access pipelines in high consequence areas (for example, cased lines at highway crossings), the following two R&D projects are recommended.

(1) *Defect Characterization*—Developing methods for defect characterization from guided–wave data would significantly enhance the usefulness of the guided-wave technology for ECDA and ICDA applications. Various groups, including SwRI, have worked on fundamental studies of guided-wave interaction with defects to understand how the defect signal changes with defect shape, size, and type so that a means to determine defect specifics could be developed from defect signals [10,13,14]. These development efforts, still in the early stages, need to be continued.

(2) *Structural Health Monitoring (SHM)*—Long-term SHM of sections of pipelines in special areas (for example, cased-lines at highway crossings) using permanently installed guided-wave probes would allow significantly better assessment of pipeline safety than a one-time survey of the line with the guided-wave inspection technology. Once installed, the condition of the pipeline can be checked any time on demand with minimal cost. Periodic checking and comparison of the newly acquired data with previously acquired data would permit accurate tracking of structural condition changes with time. Therefore, even though the specifics of the anomaly detected in the first survey could not be determined initially, comparison of the successive data enables the inspector to determine whether the structural condition is degrading with time and, if so, to determine the locations and growth rates of anomalies, thus permitting very effective DA to be made. Consisting of thin ferromagnetic strips bonded around pipe and encircling coils over the strips, the MsS is well-suited for the long-term SHM for ICDA and ECDA of pipelines in special areas. R&D needed for practical implementation of long-term SHM is recommended, including procedure development, development of data analysis methods for detecting condition changes, field validations, and technology transfer for industrial use.

6. ACKNOWLEDGMENTS

In addition to the Pipeline and Hazardous Materials Safety Administration (PHMSA), formerly the Research and Special Programs Administration (RSPA), U.S. Department of Transportation, the following members supported this project: Pipeline Research Council International, Inc. (PRCI); Southern California Gas Company (SOCAL); Gulf South Pipeline Company (GSPC); and Southwest Research Institute (SwRI). Special thanks are directed to Mr. James Merritt, PHMSA's Program Manager; PRCI and PRCI members, especially Mr. George Tinley, Dr. Keith Leewis, and Mr. Harvey Haines; Messrs. Thomas Ishii, Paul Lee, and Matt Matlas of SOCAL; and Messrs. Dan Larrington and Bruce Snow of GSPC for their support and help. Appreciation also goes to staff members at SwRI who contributed to the successful completion of the project work, including Dr. Glenn Light, Messrs. Ronald Peterson, James Crane, Robert Spinks, and Gary Hendrix, and Ms. Faye Forcum.

7. REFERENCES

1. P. Cawley, M. J. S. Lowe, D. N. Alleyene, B. Pavlakovic and P. Wilcox, "Practical Long-Range Guided-Wave Testing: Applications to Pipes and Rail," *Mat. Eval.* **61**, pp. 66–74 (2003).

2. H. Kwun, S. Y. Kim, and G. M. Light, "The Magnetostrictive Sensor Technology for Long-Range Guided-Wave Testing and Monitoring of Structures," *Mat. Eval.* **61**, pp. 80–84 (2003).

3. G. G. J. Achterbosch and M. Broderick, "NOPIG – A New Technique in Pipeline Integrity," Paper presented at the 22nd World Gas Conference held in Tokyo in June 2003.

4. M. Redwood, *Mechanical Waveguides: The propagation of acoustic and ultrasonic waves in fluids and solids with boundaries*, Pergamon Press, New York, 1960.

5. J. L. Rose, *Ultrasonic Waves in Solid Media*, Cambridge, Cambridge University Press, 1999.

6. H. Kwun and S. Y. Kim, "Torsional Guided Wave Examination of Buried Piping," Technical Report, EPRI, Palo Alto, CA: 2002. 1006308.

7. M. S. Choi, S. Y. Kim, and H. Kwun, "An Equivalent Circuit Model of Magnetostrictive Sensor for Guided Wave Applications," in Final Report on SwRI Project 14.R9404, "Development of Torsional Wave Mode Probe for Heat Exchanger Tube Inspection," Dec. 2004.

8. H. Kwun and S. Y. Kim, "Distributed, Serially Controlled, Active Sensor for Structural Health Monitoring," Final Report on SwRI Project 14.R9285, Dec. 2002.

9. R. M. Bozorth, *Ferromagnetism*, D. Van Nostrand, Inc., 1951, Chap. 13.

10. M. S. Choi, S. Y. Kim, and H. Kwun, “Transmission Line Model for Simulation of Guided-Wave Defect Signals in Piping,” *IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 51, pp. 640-643 (2004).

11. H. Kwun, S. Y. Kim, and M. S. Choi, “Experimental Comparison of Analytical Modeling of a Guided-Wave Interaction with a Notch in a Pipe,” *J. Korean Physical Society*, Vol. 45, pp. 380-385 (2004).

12. H. Kwun, S. Y. Kim, and M. S. Choi, “Reflection of the Fundamental Torsional Wave from a Stepwise Thickness Change in a Pipe,” in Final Report on SwRI Project 14.R9404, “Development of Torsional Wave Mode Probe for Heat Exchanger Tube Inspection,” Dec. 2004.

13 Y. Cho, D. D. Hongerholt, and J. L. Rose, “Lamb Wave Scattering Analysis for Reflector Characterization,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 44, pp. 44–52 (1997).

14. P. Cawley, M. J. S. Lowe, F. Simonetti, C. Chevalier, and A. G. Roosenbrand, “The variation of the reflection coefficient of extensional guided waves in pipes from defects as a function of defect depth, axial extent, circumferential extent and frequency,” *Proc. Instn. Mech. Engrs*., Vol. 216, Part C, *J. Mechanical Engineering Science*, pp. 1131–1143 (2002).