

DEVELOPMENT OF MAGNETOSTRICTIVE SENSOR TECHNOLOGY FOR GUIDED WAVE EXAMINATIONS OF PIPING AND TUBING

Sergey A. Vinogradov

Guided NDE LLC

8811 Toulouse, San Antonio, Texas, USA, Phone +1 210.464.3004

E-mail: mail@guided-nde.com

John Leonard

IHI Southwest Technologies, Inc.

6766 Culebra Rd, San Antonio, Texas, USA, Phone: +1 210.256.4101,

E-mail: jleonard@ihiswt.com

ABSTRACT

Examinations of piping and other components using guided waves have become increasingly attractive over the last decade due to high effectiveness of the technology in finding hidden anomalies. Different types of transducers together with the philosophy of a screening approach have been developed and tested using piezoelectric, and EMAT actuators.

Practical implementation of the technology has helped to recognize the most challenging applications when there is a need for better sensitivity, better inspection range, and better flaw characterization.

A review of magnetostrictive sensor technology will be given in reference to the new developmental work dedicated to the improvement of the performance of guided waves when applied to piping and tubing components.

INTRODUCTION

The concept of using guided waves for screening of piping and tubing has been progressing over the last decade. In terms of NDE techniques, the methods been classified as; long range ultrasonic testing (LRUT). The first commercially available guided wave actuators were based on both piezoelectric (1,2) and EMAT (3,4,5) transducers. Both types of actuators have a long history of use for generating of acoustic and ultrasonic vibrations.

In the family of EMAT transducers, the most cost-effective solution was based on the principle of magnetostriction utilizing *Joule-Villary*, *Widemann* and *Inversed Widemann effects*. This approach has been mostly promoted by Southwest Research Institute (SwRI) and supported via commercially available products including the electronics and the software (6).

Practical implementation of the technology clarified the need for further improvement in the following areas:

- Extending the inspection range in the presence of high attenuation
- Improving the sensitivity
- Improving the flaw characterization capability

Some of these limitations were addressed in research and development (R&D) work performed by SwRI, IHI Southwest Technologies Inc (ISwT), the Electric Power Research Institute (EPRI) and other organizations worldwide.

The predominant efforts of this R&D work were focused on long-range guided wave screening of piping and heat exchanger tubing. Figure1 and shows a typical concept of guided wave screening based on using a guided wave transducer mounted on the pipe from the outside surface (a) or placed inside of the heat exchanger tube (b).

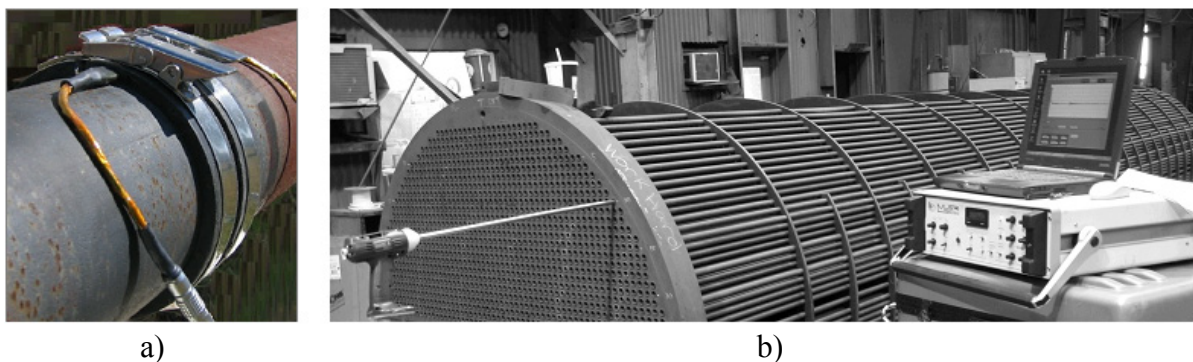


Figure 1 - Predominant applications of Magnetostrictive Sensor Technology: (a) - guided wave screening of piping; (b) guided wave screening of heat exchanger tubing

Besides these two applications, there are some other applications such as screening of plates, steel ropes, anchor rods and short-range inspection of components using guided waves.

IMPROVING THE INSPECTION RANGE

In the presence of low attenuation (in the order of 0.1 dB/m), torsional guided waves can reliably cover about 150 meters of straight run piping in each direction from the sensor.

Situations with the limited inspection range are mostly associated with these cases:

- Buried piping
- Coated piping
- Piping and tubing with thick deposits of different nature
- Piping and tubing with extensive corrosion damage.
- Finned tubing

Average attenuation rate in the above ground piping can vary from 0.01 to 1 dB/m, depending on component condition. In piping with high attenuation, the attenuation rate can be as high as 10-15 dB/m. Problems associated with limited inspection range in piping can mostly be challenged by increasing the power output of guided waves actuators. .

The first magnetostrictive guided wave actuators utilized a rather bulky array of bias magnets together with the ribbon AC circuit to generate longitudinal and torsional guided waves directly in the pipe wall. The method was limited for use only to ferromagnetic materials. A rather dramatic improvement in the performance was accomplished after utilizing a nickel strip as an actuator of torsional and longitudinal vibrations. The residual bias of the strip was serving as a substitute to a bulky array of bias magnets. Switching from nickel-based material to iron-cobalt alloys allowed for increasing the power output of the sensor by the factor of 12 dB (7). The technology has been marketed by SWRI using the trade name MsS™.

Improvements of performance of the MsS sensors were accomplished by using an embedded generator of bias magnetic field (8). The purpose of the innovation was enhanced permanent monitoring of piping using the ability to recover the permanent bias in the core of the sensor through a remote terminal. In 2007, ISwT developed a magnetostrictive transducer with the bias oriented through the width of the strip. Together with a proprietary AC circuit layout, this transducer produced significantly higher power output compared to previous MsS designs. The transducer was given a trade name MsT™ (9). Figure 2 summarizes the signal strength of magnetostrictive guided wave actuators accomplished over the last decade.

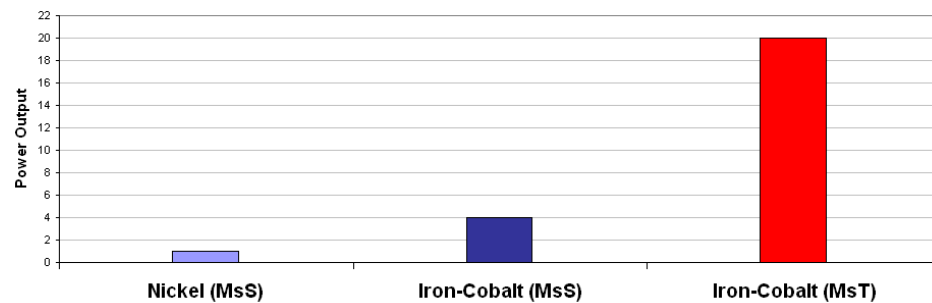


Figure 2 - Improvement in the signal strength of magnetostrictive guided wave actuators accomplished over the last decade.

Mockup testing of the transducers revealed the capability to reliably detect 10% simulated metal loss at a distance up to 13 meters on bitumen coated buried pipe with attenuation up to 10 dB/m.

Further development of MsT transducers resulted in creation of an array of products including segmented guided wave transducers, high temperature transducers and small bore torsional guided wave probes for screening of heat exchanger tubing.

Figure 3 shows MsT transducers for pipes with OD 114mm and 219 mm (left) and small bore guided wave probe for screening of heat exchanger tubes (right).

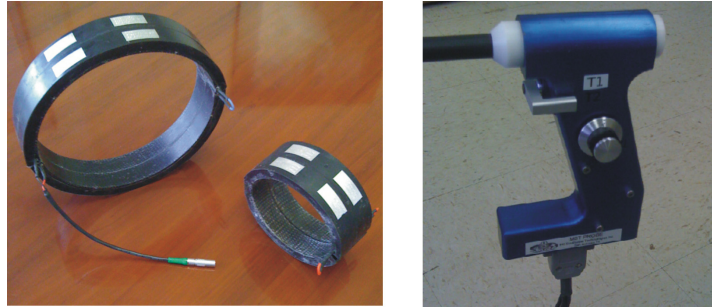


Figure 3 - MsT transducers for pipes (left) and small bore guided wave probe for screening of heat exchanger tubes (right)

Screening of exchanger tubing using guided waves turned out to be a big challenge and it took more than 10 years of developmental work before any practically acceptable results were obtained (10-15). The major problems with the tubing came from the limited space to fit the probe in, the occurrence of guided wave dumping phenomena due to the presence of numerous tube support plates and also rather high attenuation introduced by corrosion deposits. Full coverage of heat exchanger tubing was accomplished in the majority of cases using higher (above 90 kHz) frequencies of guided waves and small bore MsT transducers (16,17,18). Guided wave screening of heat exchanger tubing can offer a unique package of benefits including full coverage of U-bends, identification of wear issues under tube support plates and also detecting of cracking in the areas of rolled expansion. Figure 4 shows an example of LRUT data presentation. The data were obtained from 24 ft (8m) long heat exchanger tube after 20 years of continuous operation.

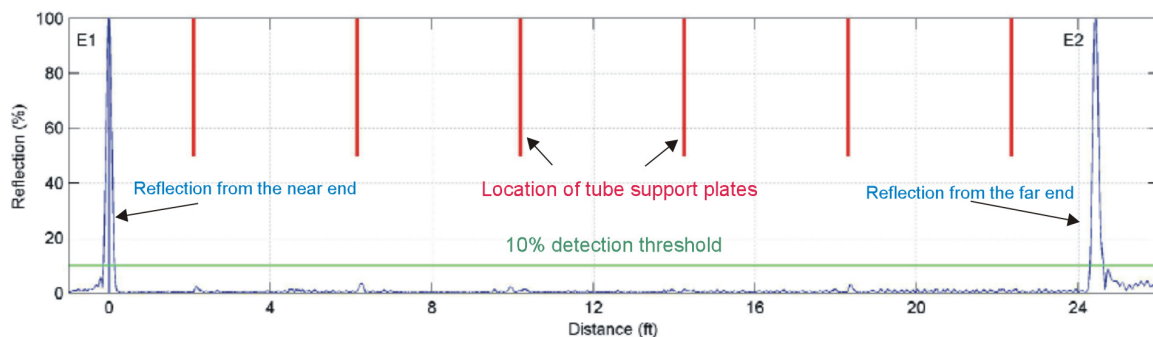


Figure 4 - Example of heat exchanger LRUT data presentation

The LRUT screening concept of heat exchanger tubing provides end-to-end coverage of the entire tube. In this particular case the accomplished signal-to-noise-ratio (SNR) allowed for the detection anomalies as small as 2% relative to the cross-section of the tube.

IMPROVING THE SENSITIVITY

The ability to recognize abnormal conditions in the component is the major reason why guided wave technology has been actively developed. The criteria of “abnormal conditions” can significantly vary from case to case and be the subject for a detailed discussion before any LRUT work takes place. Detection of gradual wall thinning, pinholes, and shallow

pitting corrosion can be quite challenging using guided waves. However, detection of axial and circumferential cracking was shown to be possible (19).

It is generally accepted that guided waves can provide a clear and a cost-effective way to determine pipe condition. A 5% detection threshold level has been generally accepted for use in delineating suspect indications from the coherent noise.

There are a few exceptions when the detection threshold should be set to higher or lower level. As an example, if the piping or tubing exhibits low level of internal reverberation then the detection threshold should be set to 1% or even less. Increasing the power output of the transducer in such a piping could also dramatically improve the SNR.

If the internal reverberation rate is high, the SNR might stay low regardless of the amount of energy introduced to a pipe. In this case, the detection threshold should be set to a higher level. The last case scenario can potentially reduce the quality of screening, but might be quite common when screening of service water piping with thick deposits. Improving the sensitivity of guided waves in the presence of high rate of internal reverberation is a challenge and continues to be developed.

Figure 5 (right) shows the typical condition of 89 mm OD service water pipe after 25 years of operation.

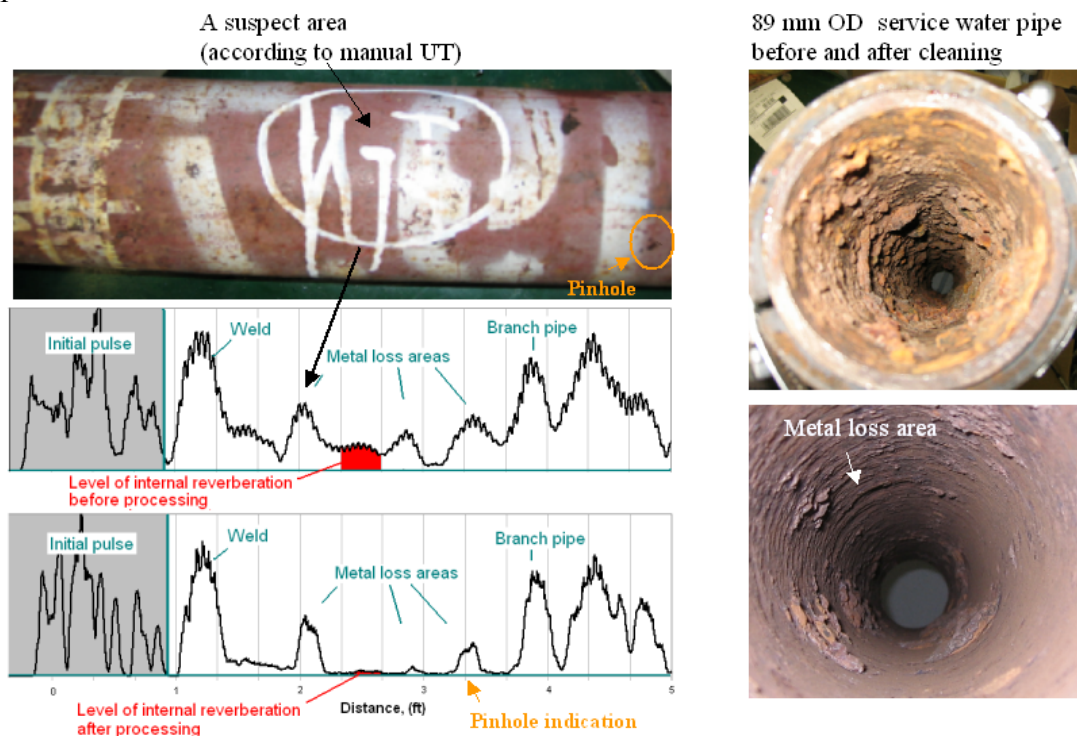


Figure 5 - Advanced LRUT screening of service water piping: Typical condition of service water pipe after 25 years of operation (right); Results of advanced conditioning of guided wave signal (left)

Like the majority of service water piping, the above pipe had rather thick deposits covering deep pockets with metal loss. Manual ultrasonic testing performed over a long period of time identified some suspect areas marked with grids and painted circle. The pipe was taken out of service after 25 years of operation as a result of leakage through the pinhole that appeared outside of the suspect area (marked with the small circle). The section of the pipe was cut off and tested in the lab using guided waves at 60 kHz. The results of initial testing and the level of internal reverberation caused by deposits are shown on the left side of the picture. It should be noted that the level of the internal reverberation would make it difficult to call any of the known metal loss indications as suspect due to rather low SNR. Improving the SNR in this case was accomplished by applying nonlinear signal processing. As a result of the advanced processing, the majority of internal reverberation signals were effectively rejected and all three indications including the indication produced by the pinhole could be detected. The approach utilizing broadband guided waves and nonlinear signal processing was shown to be very promising for a broad range of NDE applications (20).

IMPROVING THE FLAW CHARACTERIZATION

As soon as the suspect area is identified, the flaw characterization becomes of outmost importance. It is a generally accepted practice to confirm the LRUT indications with confirming NDE, like contact ultrasonic testing (UT). However, the number of indications might be rather large and all the indications need to be sorted out before any follow up NDE takes a place.

Scattering of guided waves on defects as well as the scattering on the geometry features is rather complicated phenomena. All three dimensions of a reflector – the length, the depth, and the width tend to contribute to the amplitude and to the shape of the response. There has been a great deal of R&D work done dedicated to the improvement of characterization capability of guided waves (21,22,23). It was found that using a multi-frequency approach, together with utilization of different type of focusing techniques could essentially help to clarify the geometry of the flaw.

Three types of guided waves focusing – natural, synthetic (SAFT) and dynamic (phased array) all require the use of a segmented transducer, either receiver or transmitter or both. A solenoid-type AC circuit of the MsT transducer allows a smooth transition between continuous and segmented transmission-reception of guided waves. As a result of this, every centimeter of the pipe circumference is engaged in the transmission-reception process in both ‘segmented’ and ‘full ring’ regimes.

Figure 6 shows a segmented version of MsT transducer (left) and an example of C-scan imaging of 820 mm OD flare line with stiffeners (right). It can be noticed that not only the axial position of the indication is presented but also the circumferential location and the circumferential extent.

The type of imaging used in this particular case was SAFT and it works the best when the area of interest is not too far away from the transmitter (0.5 – 10m).

The segmented transducer also allows mapping of the circumferential extent of the flaw using naturally focused flexural guided waves (24).

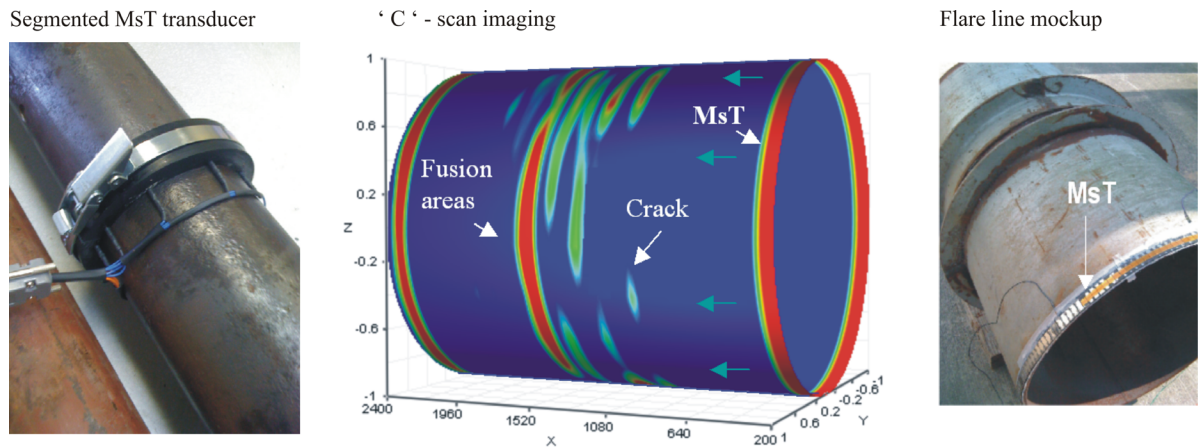


Figure 6 - Segmented version of MsT transducer (left) and an example of 'C'-scan imaging of 820 mm OD flare line mockup (right)

Figure 7 represents an example of C-scan imaging using naturally focused F(1,2) mode of guided waves in 25mm OD condenser tube. It should be noted that the majority of defects were identified and accurately mapped in the whole body of the tube with a couple of blind spots remaining. Sweeping the frequency of guided waves is typically used to cover the blind areas.

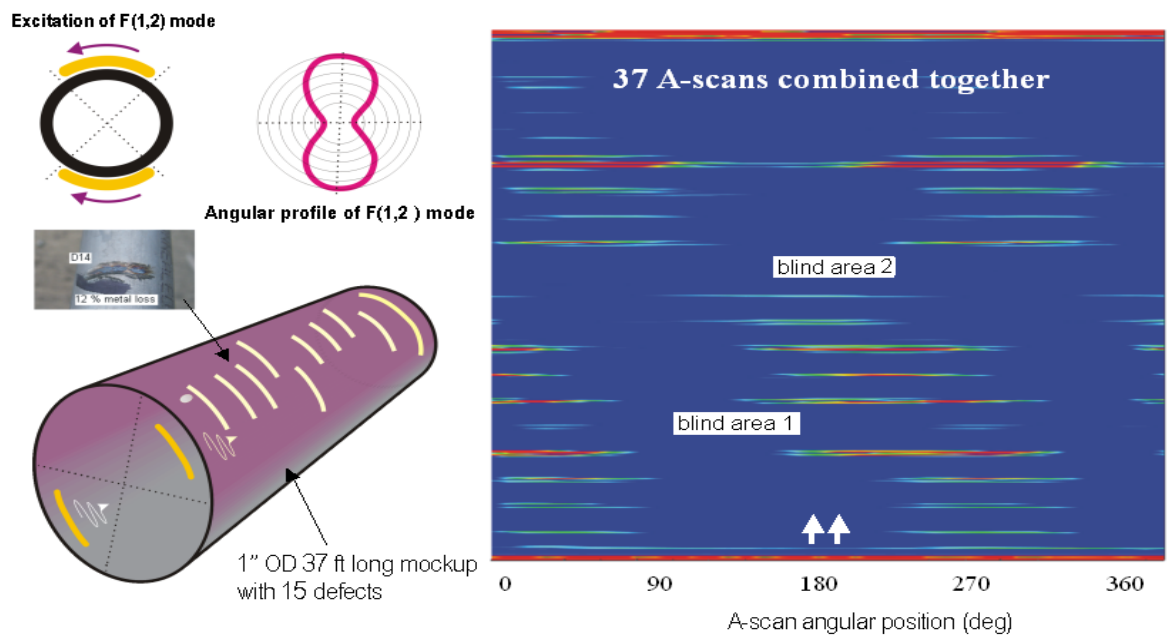


Figure 7 - C-scan imaging using naturally focused F(1,2) mode of guided waves in 25mm OD condenser tube

Focusing guided waves using segmented MsTs and phased array technique is the matter of development of appropriate electronic equipment and procedures.

CONCLUSIONS

LRUT technology has become a widely used technique for screening a variety of components. The performance and the capability of guided wave transducers has always been a key element in the successful implementation of the technology. Recent changes in the design of magnetostrictive transducers provide a significant improvement in the power output, the sensitivity and the flaw characterization. The majority of advanced techniques have been incorporated into procedures for use in the field.

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REFERENCES

1. Alleyne, D. N, and Cawley, P., 1996, 'The Excitation of Lab Waves in Pipes Using Dry-Coupled Piezoelectric Transducers,' *Journal of Nondestructive Evaluation* 15, pp. 11 – 20
2. Barshinger, J., Rose, J. L. and Avioli, M. J. Jr., 2002, 'Guided Wave Resonance Tuning For Pipe Inspection', *Journal of Pressure Vessel Technology* 124, pp. 303 - 310
3. N.S.Tzannes, “Joule and Widemann effects – the simultaneous generation of longitudinal and torsional stress pulses in magnetostrictive materials”, *IEEE transactions on Sonics and Ultrasonics*, Vol. SU-13, NO. 2, July 1966.
4. H.Kwan, C.Dynes, “Long-range Guided Wave Inspection of Pipe Using the Magnetostrictive Sensor Technology – Feasibility of Defect Characterization”, *Nondestructive evaluation of utilities and Pipelines II*, International Society for Optical Engineering, SPIE, Vol.3400, 1998, pp.326-337.
5. Kwun, H., and G.M. Light. "Magnetostrictive Sensor Technology Proven in Process Applications, *Oil and Gas Journal*, Vol. 98.21, 2000.
6. H.Kwan, S.Kim, A. Crouch. “Method and apparatus generating and detecting torsional waves for long range inspection of pipes and tubes”. U.S. Patent 6624628, 2003
7. S.Vinogradov, G.Kidd, “Advanced guided wave piping and tubing inspection using magnetostrictive sensor technology”, 5th International EPRI Conference on NDE in Relation to Structural Integrity of Nuclear and Pressurized Components, San Diego, California, 2006.
8. S.Vinogradov. “Method and System for the Generation of Torsional Guided Waves Using a Ferromagnetic Strip Sensor”. U.S. Patent 7,573,261 B1, 2009
9. S. Vinogradov, "Magnetostrictive Transducer for Torsional Mode Guided Wave in Pipes and Plates," *Materials Evaluation*, Vol. 67, N 3, 2009, pp. 333–341.
10. Ditri, J.J., J.L. Rose, F.T. Carr and W.J. McKnight, “A Novel Guided Ultrasonic Wave Technique for Improved Tubing Inspection Efficiency,” *Proceedings of the 11th International Conference on NDE in the Nuclear and Pressure Vessel Industries*, Albuquerque, New Mexico, 1992b, pp. 49–54.

11. H.J.Shin, J.L.Rose. "Guided Wave Inspection Tuning Principles for Defect Detection in Tubing," *Journal of Non-destructive Evaluation*, Vol.17 N 1, 1998
- 12.Light, G.M., C.J. Schwartz, and R.L. Spinks. "Heat Exchanger Tube Inspection Using Magnetostrictive Sensor (MsS) Technology," EPRI Balance-of-Plant Heat Exchanger NDE Symposium, Scottsdale, AZ, 2000.
13. H.Kwan, J.Crane, S.Kim, A.Parvin, G.Light, "A torsional mode guided wave probe for long range in bore testing of heat exchanger tubing" *Materials Evaluation*. 1: 430-433, 2004
14. Vogt T., Alleyne, D.N., Pavlakovic, B.N., "Application of guided wave technology to tube inspection", *Insight*, ECNDT 2006 – Th.3.1.5.
15. N. Muthu, S.Vinogradov, "Application of Guided Wave Technology for Screening of SeaCure Tubing", 6th International EPRI Conference on NDE in Relation to Structural Integrity of Nuclear and Pressurized Components, Budapest, Hungary, 2007.
16. S. Vinogradov, "Tuning of Torsional Mode Guided Wave Technology for Screening of Carbon Steel Heat Exchanger Tubing", *Materials Evaluation*, Vol. 66, N 4, 2008, pp. 419–424.
17. S.Vinogradov, N. Muthu "Development of a Screening Method for SeaCure Tubing using Guided Waves", 10th EPRI Balance-of-Plant Heat Exchanger NDE Symposium, Hyatt Regency, San Antonio, Texas, June 16-18, 2008.
18. *Nondestructive Evaluation: Guided Wave Ultrasonic Technology Applications for Balance-of-Plant Heat Exchanger Tubes and Tube Support Plate Degradation*. EPRI, Palo Alto, CA: 2008. 1016672
19. H.Kwan, S.Kim, H.Matsumoto, S.Vinogradov, "Detection of axial cracks in tube and pipe using torsional guided waves", QNDE Proceedings 2007.
20. S. Vinogradov, "Development of Enhanced Guided Wave Screening Using Broadband Magnetostrictive Transducer and Non-Linear Signal Processing ," Fourth Japan-US Symposium on Emerging NDE Capabilities for a Safer World, , Maui Island, Hawaii, USA, June 7-11, 2010 (to be published)
21. J. Rose, S. Pelts and Y. Cho, 'Modeling for Flaw Sizing Potential with Guided Waves' *Journal of Nondestructive Evaluation*, Volume 19, Number 2 / June, 2000.
22. Vinogradov, S., B. Jacobs and J. Godwin, "Experimental and Theoretical Investigation for the Use of Guided Waves to Detect and Size Corrosion/Erosion Defects in Heat Exchanger Tubes," 7th EPRI Balance of Plant Heat Exchanger NDE Symposium, Santa Ana Pueblo, New Mexico, 2002.
23. Demma, A., Cawley, P. and Lowe, M.J.S. (2003b) 'The reflection of fundamental torsional mode from cracks and notches in pipes', *J Acoust. Soc. Am.*, Vol 114, pp 611-625.
24. Rose, J.L., Sun,Z., Mudge, P.J., Avioli, M.J., "Guided wave flexural mode tuning and focusing for pipe inspection," *Materials Evaluation*, 61, pp. 162-167, 2003