TECHNICAL BACKGROUND ON MsS

Sensor Principle

- Guided wave generation—Based on the magnetostrictive (or Joule) effect
- Guided wave detection—Based on the inverse-magnetostrictive (or Villari) effect

The magnetostrictive effect refers to a small change in the physical dimensions of ferromagnetic materials—on the order of several parts per million in carbon steel—caused by externally applied magnetic field.

The inverse-magnetostrictive effect refers to a change in the magnetic induction of ferromagnetic material caused by mechanical stress (or strain).

The above effects exist only in ferromagnetic materials. The magnetostrictive effect was discovered by Joule in 1847 and the inverse effect by Villari in 1864.

Sensor Configurations, Instrumentation, and Technical Features

The sensor is configured to apply a time-varying magnetic field to the material under testing and to pick up magnetic induction changes in the material caused by the guided wave. For cylindrical objects (such as rod, tube, or pipe), the MsS is ring-shaped to encircle the object. For plate-like objects, the MsS is rectangular-shaped to be placed on the surface of the object.

A schematic diagram of the MsS and associated instruments for generation and detection of guided waves is shown in Figure 1. The MsS instrument is composed of a transmitter section and a receiver section. To allow the directionality control of the generated and detected guided wave signals, the MsS instrument contains two transmitters and two receivers. The output signals of the receiver section are displayed on a digital oscilloscope (with MsSR-2020) or on a laptop computer (with MsSR-2020D).

To operate the MsS, the material under testing needs to be in a magnetized state. This is achieved by applying a DC bias magnetic field to the material using either permanent magnet, electromagnet, or residual magnetization induced in the material. The DC bias magnetization is necessary to enhance the transduction efficiency of the sensor (from electrical to mechanical and vice versa) and to make the frequencies of the electrical signals and guided waves the same. The transduction efficiency of the MsS increases initially with increasing DC bias magnetic field level, reaches a maximum, and then decreases with further increase in the DC bias magnetic field level, as illustrated in Figure 2. The optimum DC bias magnetic field is typically the level just below the knee of the magnetization curve of the material under testing.

Technical features of the MsS include:

- Requires no couplant
- Can be operated with a gap to the material under testing
- Is broadband
- Has a good sensitivity in frequencies up to a few hundred kHz

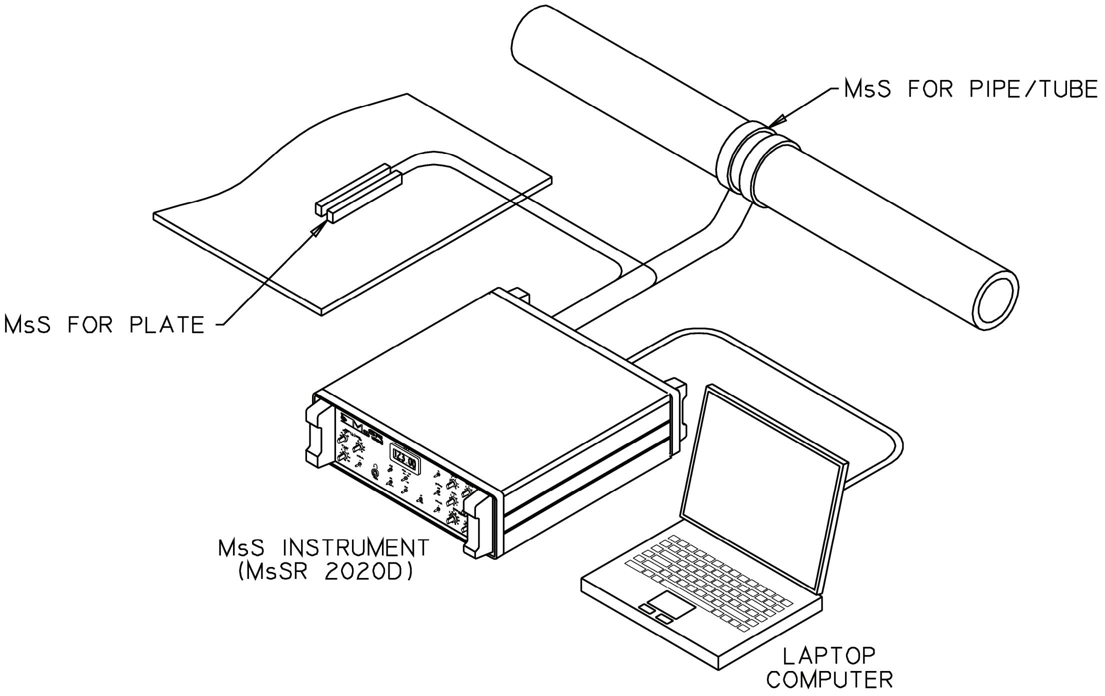


Figure 1. Schematic diagram of the MsS and associated instruments

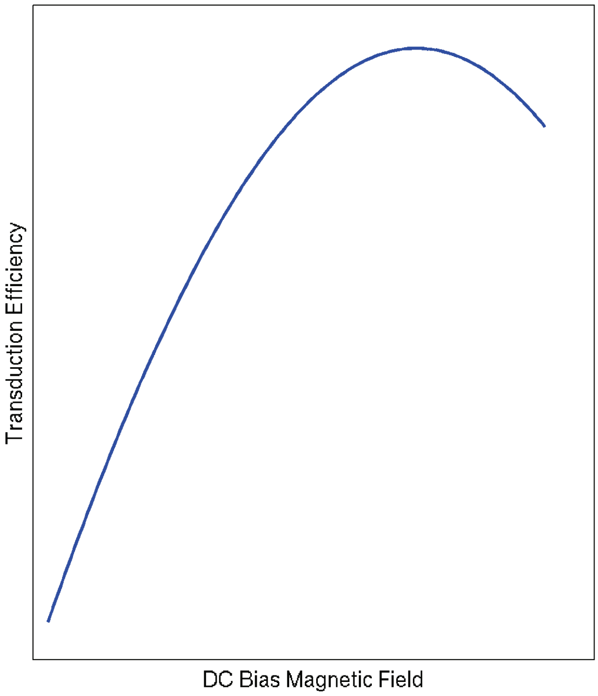


Figure 2. Transduction efficiency versus DC bias magnetic field level

Applicable guided wave modes are:

- Longitudinal, torsional, and flexural wave modes in cylindrical objects
- Symmetric and antisymmetric Lamb wave and shear horizontal wave modes in plates.

The operating wave mode of the MsS is controlled by the relative alignment between the DC bias magnetic field and the time-varying magnetic field produced by the MsS. For longitudinal wave modes in cylindrical objects and Lamb wave modes in plates, a parallel alignment is used. For torsional wave modes in cylindrical objects and shear horizontal wave modes in plates, a perpendicular alignment is used.

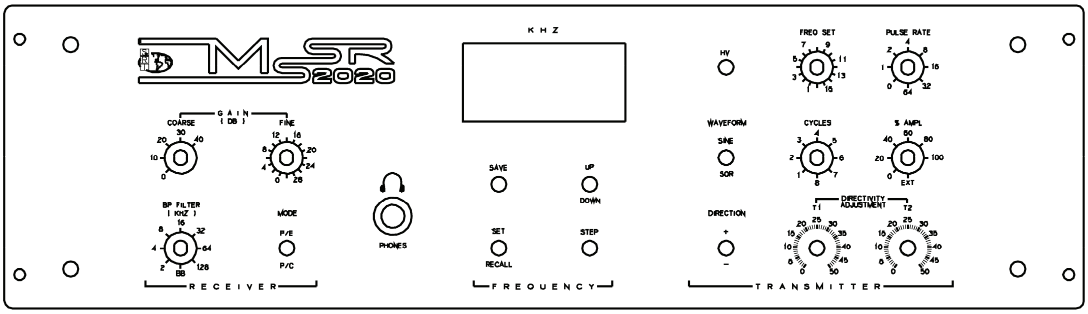
Application to Nonferrous Materials—Thin-Ferromagnetic-Strip Approach

Since the MsS relies on magnetostrictive effects, it is applicable only to ferrous materials such as carbon steel, alloy steel, and ferritic stainless steel (300 series). However, application of the MsS can be easily extended to nonferrous materials (such as aluminum) by bonding a thin strip of ferromagnetic material (such as nickel) to the nonferrous material and operating the MsS over that strip. In this case, the MsS generates the guided waves in the strip. The generated guided waves are then mechanically coupled to the nonferrous material and propagate. Detection of the guided waves is achieved in the reverse manner.

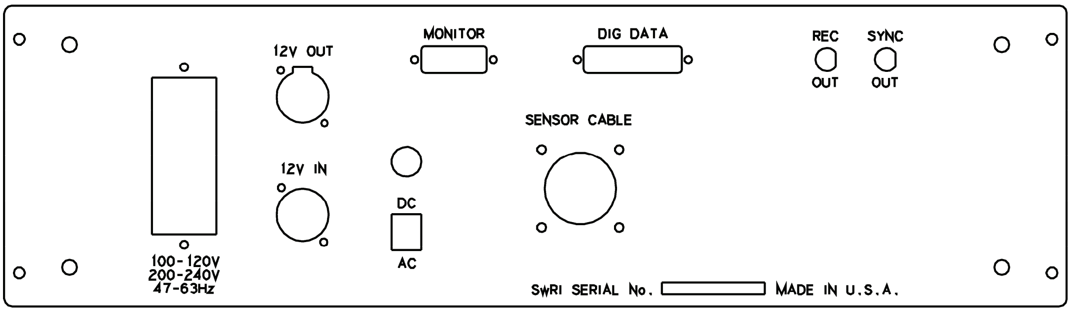
This thin-ferromagnetic-strip approach is also very useful for generating and detecting guided waves in ferrous materials. Advantages of this approach over direct generation and detection in ferrous materials are (1) higher MsS sensitivity and (2) no need to magnetize the ferrous material under testing. The thin-ferromagnetic-strip approach is particularly useful for long-range torsional wave inspection of piping and shear horizontal wave inspection of plate.

MsS INSTRUMENT (Model MsSR 2020) AND SPECIFICATIONS

Front View



Rear View



Specifications

Transmitter:

Outputs:	Two HV differentially driven synchronous burst type outputs. May be operated in-phase or with ±90-degree phase displacement (for directionality control)
Waveforms:	Sine or square
No. of Cycles:	1–8 selectable
Output Voltage:	300 Vpp max.
Output Current:	40 App max.
Output attenuation:	0 to 100% in 20% steps
Frequency:	2 to 250 kHz with 500-Hz resolution
PRF rate:	1 to 64 pps in binary increments
Ext. Sync:	TTL compatible, neg. edge justified
Setup monitor:	Switch settings readable by PC

Receiver:

Inputs:	Two HV protected differential inputs summed together. Prior to summation, the signals may be electronically phase shifted ±90 degrees (unidirectional capability).
Gain:	110 dB max. overall 40 dB fixed gain standard (internally adjustable) 0–40 dB coarse gain (10-dB steps) 0–30 dB fine gain (2-dB steps)
Filters:	8 individual 4-pole active filter modules Standard designs span frequency range. (Other LP, HP, or BP designs can be provided for special applications.)
Signal Output:	Analog waveform, ±3V max. into 50 ohms
Output Impedance:	50 ohms
Setup monitor:	Switch settings readable by PC
Optional Digital Signal Outputs:	12 bits, parallel interface (for Model MsSR 2020D)
Operating Modes:	Pulse-echo or pitch-catch

Power:

MsS Unit:	90–264V, 50/60 Hz

Environmental Conditions:

Temperature:	+5 to +122 deg. F (operating) -15 to +50 deg. C -4 to +140 deg. F (storage) -20 to +60 deg. C
Humidity:	10 to 80 % rel. hum. (operating) 5 to 95 % rel. hum. (storage) Noncondensing

Enclosure:

Dimensions:	18.2" (46.3 cm) d x 18.5" (47.1 cm) w x 5.8" (14.7 cm) h without end covers Add 3.5" (8.9 cm) to depth with end covers installed. Tip-up handle also included.
Weight:	31.5 lbs (14.3 kg)

PATENTS AND PUBLICATIONS

U.S. Patents on MsS (as of January 25, 2002)

1. Patent No. 5,456,113, "Nondestructive Evaluation of Steel Cables and Ropes Using Magnetostrictively Induced Ultrasonic Waves and Magnetostrictively Detected Acoustic Emissions," (issued in October 1995).
2. 2. Patent No. 5,457,994, "Nondestructive Evaluation of Non-ferromagnetic Materials Using Magnetostrictively Induced Acoustic/Ultrasonic Waves and Magnetostrictively Detected Acoustic Emissions," (issued in October 1995).
3. Patent No. 5,581,037, "Nondestructive Evaluation of Pipes and Tubes Using Magnetostrictive Sensors," (issued in December 1996).
4. Patent No. 5,767,766, "Apparatus and Method for Monitoring Vehicular Impacts Using Magnetostrictive Sensors," (issued in June 1998).
5. Patent No. 6,205,859, "Method for Improving Defect Detectability with Magnetostrictive Sensors for Piping Inspection," (issued in March 2001).
6. Patent No. 6,212,944, "Apparatus and Method for Monitoring Engine Conditions Using Magnetostrictive Sensors," (issued in April 2001).
7. Patent No. 6,294,912, "Method and Apparatus for Nondestructive Inspection of Plate-Type Structures Using Magnetostrictive Techniques," (issued in September 2001).
8. Patent No. 6,295,677, "Method for Inspecting Liquid Filled Pipes Using Magnetostrictive Sensors," (issued in October 2001).

Pending Patents

1. "Measurements of Torsional Dynamics of Rotating Shafts Using Magnetostrictive Sensors," (U.S. Patent Application Serial No. 09/355,177; Filed in July 1999).
2. "Method and Apparatus for Short Term Inspection or Long Term Structural Health Monitoring," (U.S. Patent Application Serial No. 09/855,460; Filed in March 2001).
3. "Method for Inspecting Electric Resistance Welds Using Magnetostrictive Sensor," (U.S. Patent Application Serial No. 09/519.530; Filed in February 2000).
4. "Method and Apparatus Generating and Detecting Torsional Waves for Inspection of Pipes or Tubes," (U.S. Patent Application Serial No. 09/815,219; Filed in March 2001).
5. "Method and Apparatus Generating and Detecting Torsional Waves for Long Range Inspection of Pipes or Tubes," (U.S. Patent Application Serial No. 09/815,017; Filed in March 2001).
6. "A Method and Apparatus for Inspecting Pipelines from an In-Line Inspection Vehicle," (U.S. Patent Application Serial No. 09/738,062; Filed in December 2000).

7. “Time-Shift Data Analysis for Long-Range Guided Wave Inspection,” (Filed in January 2002).

Publications on MsS

1. H. Kwun, J. J. Hanley, and C. M. Teller, “The Performance of a Noncontact Acoustic Emission Sensor on a Cylindrical Steel Rod,” *J. Acoustic Emission* **11**, pp. 27-32 (1993).

2. C. M. Teller and H. Kwun, “Magnetostrictive Sensors for Structural Health Monitoring Systems,” *Proc. 48th Meeting of the Mechanical Failures Prevention Group*, April 19-21, 1994, Wakefield, Massachusetts (compiled by H. C. Pusey and S. C. Pusey, Vibration Institute, Willowbrook, Illinois, 1994), pp. 297-305.

3. H. Kwun and C. M. Teller, “Detection of Fractured Wires in Steel Cables Using Magnetostrictive Sensors,” *Material Evaluation* **52**, pp. 503-507 (1994).

4. C. M. Teller and H. Kwun, “New Methods for Inspecting and Monitoring Bridge Structures Using Magnetostrictive Sensors,” *Review of Progress in Quantitative NDE, Vol. 13*, edited by D. O. Thompson and D. E. Chimenti (Plenum, New York, 1994) pp. 2147-2153.

5. H. Kwun and C. M. Teller, “Magnetostrictive Generation and Detection of Longitudinal, Torsional, and Flexural Waves in a Steel Rod,” *J. Acoustic. Soc. Am*. **96**, pp. 1202-1204 (1994).

6. H. Kwun, “Back in Style: Magnetostrictive Sensors,” *Technology Today* (Southwest Research Institute, March 1995), pp. 2-7.

7. H. Kwun and K. A. Bartels, “Experimental Observation of Wave Dispersion in Cylindrical Shells Via Time-Frequency Analysis,” *J. Acoustic. Soc. Am*. **97**, pp. 3905-3907 (1995).

8. H. Kwun, J. J. Hanley, and A. E. Holt, “Detection of Corrosion in Pipe Using the Magnetostrictive Sensor Technique,” *Proc. International Society for Optical Engineers (SPIE) on Nondestructive Evaluation of Aging Maritime Applications*, edited by R. B. Mignogna, SPIE Vol. 2459, pp. 140-148 (1995).

9. H. Kwun and A. E. Holt, “Feasibility of Underlagging Corrosion Detection in Steel Pipe Using the Magnetostrictive Sensor Technique,” *NDT&E International* **28**, pp. 211-214 (1995).

10. H. Kwun and K. A. Bartels, “Experimental Observation of Elastic Wave Dispersion in Bounded Solids of Various Configurations,” *J. Acoustic. Soc. Am*. **99**, pp. 962-968 (1996).

11. H. Kwun and J. J. Hanley, “Long-Range, Volumetric Inspection of Tubing Using the Magnetostrictive Sensor Technique,” *Proc. 4th EPRI Balance-of-Plant Heat Exchanger NDE Symposium*, June 10-12, 1996, Jackson Hole, Wyoming.

12. H. Kwun, J. J. Hanley, and K. A. Bartels, “Recent Development in NDE of Steel Strands and Cables Using Magnetostrictive Sensors,” *Oceans 96 MTS/IEEE Proceedings*, pp. 144-148 (Sept. 23-26, 1996, Fort Lauderdale, Florida).

13. K. A. Bartels, H. Kwun, and J. J. Hanley, "Magnetostrictive Sensors for Characterization of Corrosion in Rebars and Prestressing Strands," *Proc. SPIE on Nondestructive Evaluation of Bridges and Highways*, edited by S. B. Chase, SPIE Vol. 2946, pp. 40-50 (1996).

14. T. Gioustsos and H. Kwun, "The Use of Magnetostrictive Sensors for Vehicle Safety Applications," SAE Paper No. 970774 (February 1997).

15. K. A. Bartels, C. Dynes, and H. Kwun, "NDE of Prestressing Strands with Magnetostrictive Sensors," *Proc. SPIE on Structural Materials Technology III – An NDT Conference*, edited by R. D. Medlock and D. C. Laffrey, SPIE Vol. 3400, pp. 326-337 (1998).

16. H. Kwun and C. Dynes, "Long-Range Guided Wave Inspection of Pipe Using the Magnetostrictive Sensor Technology – Feasibility of Defect Characterization," *Proc. SPIE on NDE of Utilities and Pipelines II*, edited by W. G. Reuter, SPIE Vol. 3398, pp. 28-34 (1998).

17. H. Kwun and K. A. Bartels, "Magnetostrictive Sensor Technology and Its Applications," *Ultrasonics* **36**, pp. 171-178 (1998).

18. H. Kwun, K. A. Bartels, and J. J. Hanley, "Effects of Tensile Loading on the Properties of Elastic-Wave Propagation on a Strand," *J. Acoustic. Soc. Am.* **103**, pp. 3370-3375 (1998).

19. K. A. Bartels, C. Dynes, Y. Lu, and H. Kwun, " Evaluation of Concrete Reinforcements Using Magnetostrictive Sensors," *Proc. SPIE on NDE of Bridges and Highways III,* edited by S. B. Chase, SPIE Vol. 3587, pp. 210-218 (1999).

20. H. Kwun, K. A. Bartels, and C. Dynes, "Dispersion of Longitudinal Waves Propagating in Liquid-Filled Cylindrical Shells," *J. Acoustic. Soc. Am.* **105**, pp. 2601-2611 (1999).

21. H. Kwun and G. M. Light, "Magnetostrictive Sensor Technology Proven in Process Applications," *Oil & Gas Journal*, pp. 77-79 (May 22, 2000).

22. H. Kwun and S. Y. Kim, "Long-Range Guided-Wave Inspection of Steel Plates Using Magnetostrictive Sensors," *Proc. 2nd International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, Vol. 3*, pp. C421-C435 (EPRI, Palo Alto, California, 2000).

23. D. A, Khazem, H. Kwun, and S. Y. Kim, "Long-Range Inspection of Suspender Ropes in Suspension Bridges Using the Magnetostrictive Sensor Technology," *Proc. 3rd International Workshop on Structural Health Monitoring: the Demands and Challenges* (Sept. 12-14, 2001, Stanford University, California), edited by F. Chang (CRC Press, Bota Raton, 2001), pp. 384-392.

24. H. Kwun, S. Y. Kim, and G. M. Light, "Long-Range Guided Wave Inspection of Structures Using the Magnetostrictive Sensor," *J. Korean Soc. for Nondestructive Testing* **21**, pp. 383-390 (2001).