Review of Guided Wave Testing Using Magnetostrictive Transducers

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Abstract

The use of guided waves for long-range inspection of components is a rapidly growing segment of the NDE service business. Magnetostrictive sensors utilizing ferromagnetic strip material for the transduction effect have proven to be very effective for guided wave testing on a variety of components. There is still a demand for enhanced sensor characterization and the development of specific sensor characteristics. A novel magnetostrictive transducer (MsT) utilizing a reversed Wiedemann effect was introduced to the market in 2010 [1] and opened a number of new possibilities in guided wave testing. The most challenging area is structural health monitoring of components operating at elevated temperature. An extremely robust transducer design was developed and tested for this application; it is capable of functioning at high temperatures as well as stresses induced by thermal cycling. Another recent development is an automated omnidirectional probe suitable for screening of large shells such as storage tank walls or bottoms. A number of additional specialized applications of MsTs are presented including testing of boiler tubes, heat exchanger tubes, and buried anchor rods. Performance of the MsT and its limitations for each particular application will be discussed.

Keywords: Guided wave testing, MsT, magnetostrictive transducers, structural health monitoring, high temperature pipes, anchor rods, reversed Wiedemann effect

INTRODUCTION

Magnetostrictive sensors have been proven to be very effective for guided wave testing of pipes and plates [2,3]. However, there is still a great demand for enhanced sensor characteristics or specific requirements for sensor design, compared to what is possible with most conventional guided wave sensors. For example, some applications require especially low profile or small size sensors [4]. Another example is the need for sensors for structural health monitoring (SHM) of components operating at elevated temperatures [5,6]. A very robust sensor design is needed that is capable of surviving high temperatures as well as the stresses induced by thermal cycling. A third example is guided wave testing of components with high attenuation, such as buried or coated pipes or anchor rods, for which higher transmitted signal amplitudes would be very beneficial [7,8]. This paper describes applications of guided wave transducers utilizing the effect of magnetostriction for generation of shear and torsional guided waves. These types of transducers fit well to the ‘high challenge’ areas described above. Because there is a large number of magnetostrictive transducers and some of them have novel designs, the authors will classify them based on physical principles.

WIEDEMANN EFFECT AND MAGNETOSTRICTIVE EMATS

The Wiedemann effect was discovered more than a century ago by Gustav Wiedemann [9]. The general definition is the twisting of a ferromagnetic rod when an electric current is passed down its length (creating a circumferential magnetic field) while the rod is simultaneously placed in a longitudinal magnetic field. One common use of this effect is the generation of torsional guided wave modes by having one of these fields be time-varying in rod structures. Figure 1 shows two alternative implementations of the Wiedemann effect: a) permanent circumferential field (propagation perpendicular to this bias) – the conventional Wiedemann effect, and b) time-varying circumferential field (propagation parallel to the axial bias) – a reversed Wiedemann effect.

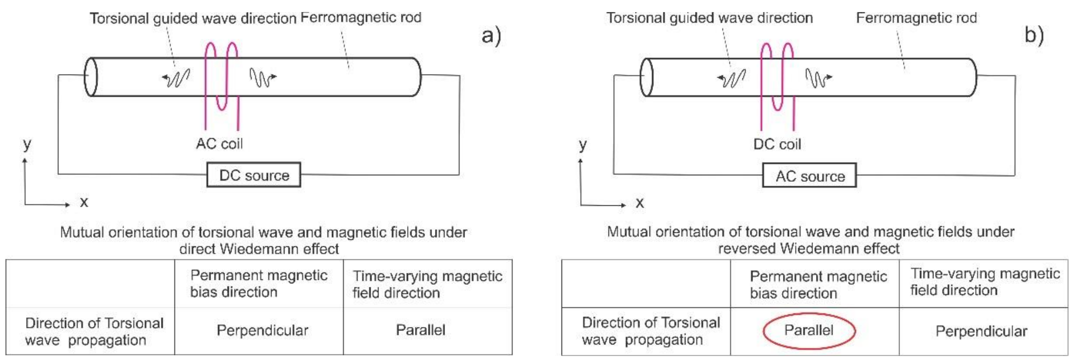

Figure 1. Two alternative implementations of Wiedemann effect: a – direct Wiedemann effect when the circumferential field is permanent and b - a reversed Wiedemann effect when the circumferential field is time-varying.

Inherently, direct and reversed Wiedemann effect Electro Magnetic Acoustic Transducers (EMATs) have exactly the same principal coil arrangement: one coil/conductor providing a time varying magnetic field perpendicular to a coil/magnet providing a magnetic bias, with both coils generating in-plane magnetic fields. What makes the difference in sensor design is how these two coils are oriented in the wave propagation direction. In a Wiedemann effect EMAT, the magnetic bias direction is parallel to the wave propagation direction.

MAGNETOSTRICTIVE EMATS AND MSTS FOR PLATES

A segment of a plate or shell is shown in Figure 2. Development of magnetostrictive EMATs for shells (including cylindrical shells) was conducted by Thompson [10] and Bobrov [11], with the majority of the probes utilizing propagation of transverse vibrations perpendicular to the magnetic bias (shear horizontal wave 1 in Figure 2).

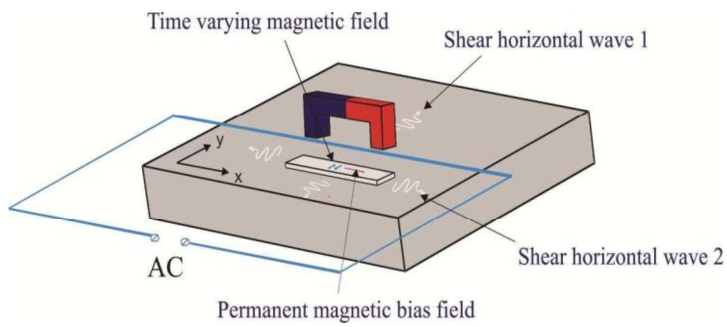

Figure 2. A configuration to generate shear waves propagating in orthogonal directions using two orthogonal magnetic fields.

This type of field arrangement is predominant in commercial EMATs; it has been used in NDE systems since the 1970s. A meander coil used with these EMATs significantly amplifies the wave propagating in the wanted direction at the desired wavelength determined by coil line separation. Less common is the reversed Wiedemann effect coil configuration with the wave propagation direction parallel to the magnetic bias (shear horizontal wave 2 in Figure 2). The reason why this coil design is not widely used is difficulty in using a meander coil. It should be noted that this coil orientation is utilized in PPM (periodic permanent magnet) EMATs, but these EMATs use the Lorenz force rather than magnetostriction [12]. Even though a reversed Wiedemann effect transducer is less common in practical NDE, its application to ferromagnetic strip sensors have resulted in the creation of a great number of different types of magnetostrictive transducer (MsT) with excellent performance [13-14]. Difficulty in using a meander coil in MsTs has been overcome. By utilizing two transducers, each with multiple segments, direction control capability has been achieved; amplitude ratios between signals traveling in the wanted and unwanted directions can reach 25 – 30 dB. Figure 3a shows a direct Wiedemann/Thompson effect probe with two quarter wavelength spaced meander coils (each coil has two channels separated by one half of the wavelength). Figure 3b shows a MsT probe (reversed Wiedemann effect) with two quarter wavelength spaced transducers (each transducer has two segments also separated by half of the wavelength to reject unwanted directions).

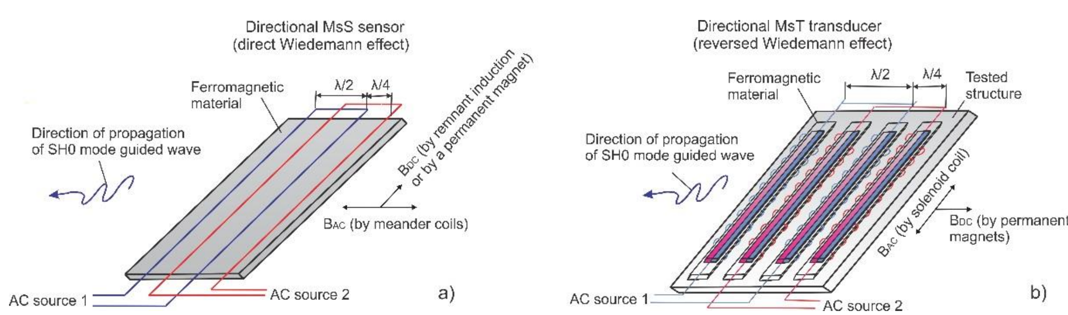

Figure 3. Directional transmission of guided waves: a – utilizing two quarter wavelength spaced meander coils (each coil has two conductors separated by half of the wavelength); b – utilizing two quarter wavelength spaced MsT transducers (each transducer has two channels separated by half of the wavelength, connected to reject the unwanted direction).

As seen in the figure, MsT design is somewhat more complicated than direct Widemann sensors. However, MsTs have the following unique characteristics: 1) the ability to use smaller rare earth permanent magnets to achieve uniform and stable bias fields, 2) the choice of more efficient electric coil arrangements to induce a stronger time-varying magnetic field for a given coil impedance, 3) capability to generate nonlinear operating characteristics using high strength magnetic fields, and 4) the ability to generate unidirectional guided waves when the field arrangement is combined with a magnetically soft ferromagnetic strip (patch). These unique properties of MsTs were investigated in detail [15,16]. Examples of MsT and EMAT probes used to provide guided wave inspection of hidden regions of nuclear reactor containment vessels is shown in Figure 4.

Figure 4. MsT (left) and EMAT (right) for guided wave inspection of containment vessels

MsTs FOR SHM OF ELEVATED TEMPERATURE PIPES

First evaluation of MsTs on full scale mockup was conducted on 219 mm OD schedule 40 pipe was supported by BP [17]. With the target operating temperature of 200°C, the mockup allowed accurate temperature control, thermal cycling, and pressure variation by the use of pressurized water inside (a sketch of the mockup is shown in Figure 5). Testing was conducted during 270 days with variable temperatures and multiple thermal cycles applied to the probe. The MsT probe (shown in Figure 5a) was bonded to the pipe. It was assumed that it would eventually de-bond and surface traction forces would be supported by the installed retention clamp. As a result of the test, it was experimentally confirmed that the probe was able to deliver very reproducible A-scan traces when data were acquired at similar temperatures. As an example, Figure 5b shows overlapped A-scan traces received at day 50 at 190°C (red) and day 217 at 202°C (green). Results of baseline subtraction are shown in black. It should be noted the temperature difference between these two days was 12°C and these two traces are nearly identical. The average signal to noise ratio (SNR) of the test data was in the range of 44 – 47 dB at frequencies of 60-90 kHz. This SNR allowed detection of a 1.5% crosssectional area anomaly in an open span of the pipe before applying the baseline subtraction algorithm (BSA). Applying BSA allowed suppression of the majority of signals related to pre-existing conditions by 23 dB. The best data reproducibility over time was accomplished at close to identical temperature regimes due to variations in acoustic coupling. Random fluctuations of coherent noise were found to be at a level of 0.4%.

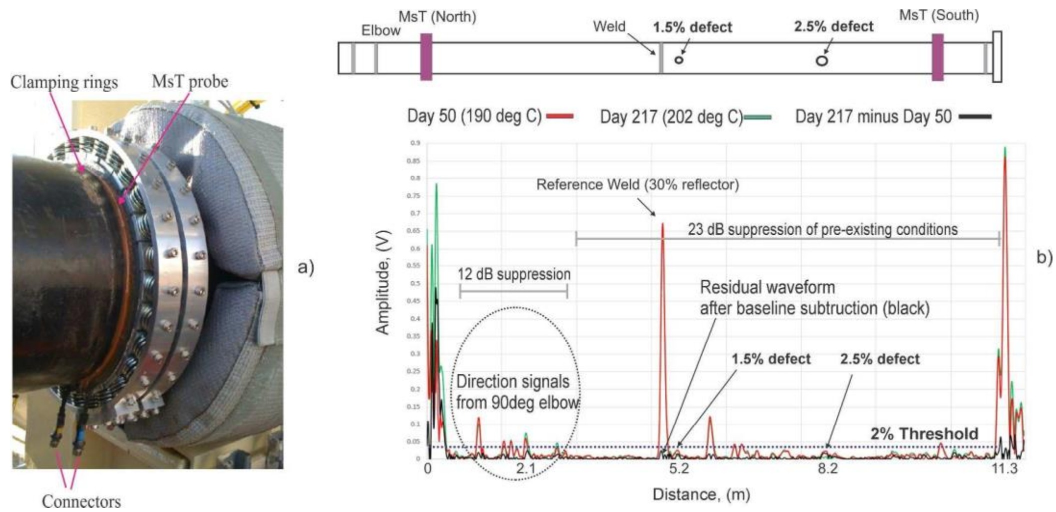

Figure 5. Results of MsT testing on 219 mm OD schedule 40 pipe: a – probe setup with bonded MsT and a retention clamp, b – overlapped A-scan traces at day 50 at 190°C (red) and day 217 at 202°C (green). Results of baseline subtraction are shown in black.

To expand the temperature range of MsTs to 500°C, a version of the MsT utilizing an electromagnet bias field generator, a crimped strip approach and high temperature clamp was developed [18-20]. This probe can be dry coupled to a pipe surface, does not have any electrical joints, and has the ability to compensate for the stresses caused by thermal cycling due to the presence of crimped areas in the ferromagnetic strip. The SNR accomplished using this transducer was lower (about 36 - 40 dB) than transducers developed for lower temperatures, but should be suitable for practical structural health monitoring (SHM) applications.

OMNIDIRECTIONAL MAGNETOSTRICTIVE TRANSDUCERS

Omnidirectional coverage can be accomplished by rotating a unidirectional probe and acquiring data at multiple circumferential positions. The rotation is provided by a servo motor, with data acquired at 1 to 5 degree angular increments. Issues with durability and probe acoustic coupling were resolved by utilizing a protective metal shell between the probe and the tested structure, and shear wave couplant. This probe was developed for automated guided wave scanning of large shells, such as storage tank walls and bottoms, with a target area of coverage of the order of 100 square meters from one probe position [21]. A possible application is screening of pipe supports. Figure 6a shows an MsT 360 probe mounted on a 609 mm OD, 7 mm wall carbon steel pipe. The pipe was taken out of service; it had wide spread pitting corrosion with the depths of 0.5 – 3.7 mm. From a 5 minute 360-degree scan using 150 kHz, all visible pitting corrosion produced indications after applying synthetic aperture focusing (SAFT), as shown in Figure 6b.

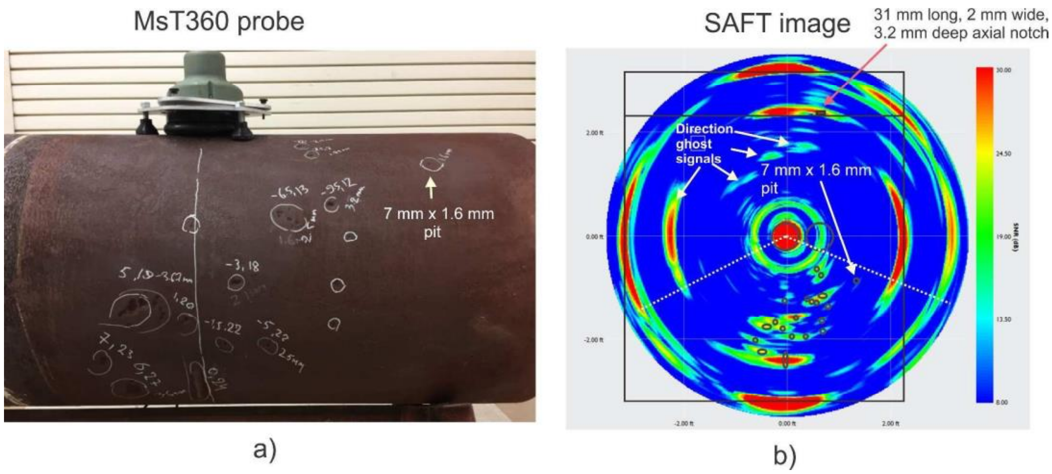

Figure 6. a- MsT 360 probe mounted on top of a 609 mm OD, 7 mm wall carbon steel pipe, b – SAFT imaging of tested structure using 150 kHz shear horizontal guided waves.

A notch in the seam weld (not visible in the photo) also produced an indication, as shown in Figure 6b. The energy reflected by the seam weld in this case was backscattered away from probe, so there is no reflected signal from the weld. Data acquired at 150 kHz using SH0 helical pass guided wave were presented, however, the probe can be configured for operation at a wide variety of frequency ranges between 20 – 500 kHz. The current version of the probe is well suited to applications based on guided wave screening. The future advancements of this technology will include reducing the dimensions of the probe to make it more suitable for SHM applications.

GUIDED VAVE TESTING OF BURIED ANCHOR RODS, BOILER TUBING AND HEAT EXCHANGER TUBING

GWT of buried anchors

Guided wave testing of buried anchor rods using MsTs and torsional guided waves was recently investigated. The major goal was simplifying probe setup, accomplishing higher sensitivity and greater axial resolution. For this application, MsTs were configured for operation at 20 – 90 kHz. Figure 7a shows an MsT dry coupled to 56 mm OD anchor rod. An A-scan acquired from a buried anchor in good condition is shown in Figure 7b. The presence of a reflection from the end of the anchor and absence of any large indications in the buried section confirm that this anchor is in good condition. Figure 7c shows an A-scan obtained from another anchor. The absence of an end reflection and the presence of large indications in the middle section lead to a conclusion that this anchor has substantial generalized corrosion. The method is qualitative, allowing ranking into good, medium, and bad categories. If the anchor has a long region covered by concrete, then the guided wave penetration will be limited to about a meter or less.

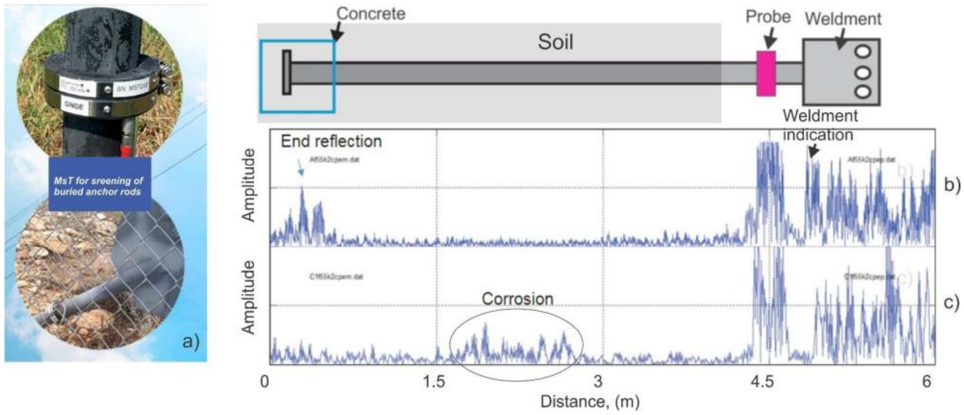

Figure 7. Testing of buried anchor rods using MsTs: a – a transducer dry coupled to 56 mm OD anchor rod, b – data acquired from a buried anchor in good condition at 50 kHz, c – data acquired from an anchor with localized corrosion at 50 kHz.

GWT of heat exchanger tubes

Since 2004, several different types of probes were developed for ferromagnetic and non-ferromagnetic tubing (the probes are shown on Figure 8a). Field testing on carbon steel (CS) tubing indicated that higher frequencies (128 kHz) provided better penetration under tube support plates and better ability to penetrate past U-bends [22]. It was also found that some heat exchanger tubes did not support guided wave propagation, and sometimes indications produced by tube support plates (TSP) had multiple reflections that make analysis complicated. Other field trials conducted on oil lube cooler with SeaCure tubing were successful [23]. Overall, application of guided waves for screening of heat exchanger tubing was found to be very challenging; the SNR can vary from excellent to poor depending on tube conditions.

GWT of boiler tubes

MsTs for GWT of boilers were developed for detection of axial cracking caused by explosive cleaning and generalized corrosion. Two types of probes were developed, one with side coverage of boiler tubes (Figure 8b) and another claw type probe allowing clamping around the tube (Figure 8c). A probe with partial coverage is more suitable for water-wall tubing when the only access is from the hot side. During experimental work, it was shown that a set of four anomalies, each with 1% cross-sectional area, on the cold side of a mockup at a distance of 1 meter from the probe could be detected. It was shown that these anomalies could be detected effectively based on +6 dB criteria at frequencies of 80–170 kHz [24]. Field testing of the probe indicated that a test range plus minus 2 meters from one probe position could be accomplished using 130 kHz frequency with the speed of data acquisition about 30 sec per tube. The test was conducted on tubes with a refractory in place.

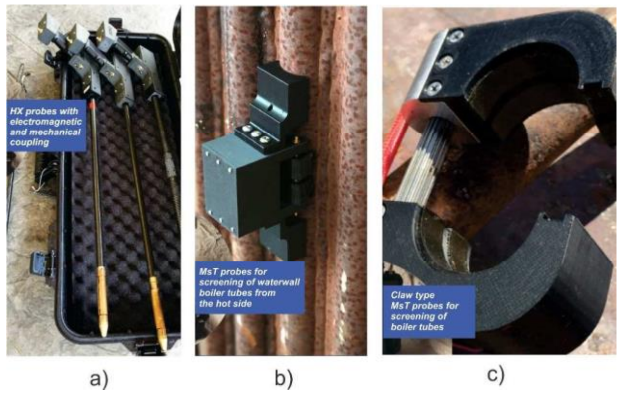

Figure 8. Ruggedized MsT probes: a - for GWT of HX tubing with electromagnetic and mechanical coupling, b – for GWT of water-wall boiler tubing, c - claw type probe for GWT of boiler tubing.

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