Designation: E1774 – 17 (Reapproved 2022)

Standard Guide for
Electromagnetic Acoustic Transducers (EMATs)[1]

This standard is issued under the fixed designation E1774; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This guide is intended primarily for tutorial purposes. It provides an overview of the general principles governing the operation and use of electromagnetic acoustic transducers (EMATs) for ultrasonic examination.

1.2 This guide describes a non-contact technique for coupling ultrasonic energy into an electrically conductive or ferromagnetic material, or both, through the use of electromagnetic fields. This guide describes the theory of operation and basic design considerations as well as the advantages and limitations of the technique.

1.3 This guide is intended to serve as a general reference to assist in determining the usefulness of EMATs for a given application as well as provide fundamental information regarding their design and operation. This guide provides guidance for the generation of longitudinal, shear, Rayleigh, and Lamb wave modes using EMATs.

1.4 This guide does not contain detailed procedures for the use of EMATs in any specific applications; nor does it promote the use of EMATs without thorough testing prior to their use for examination purposes. Some applications in which EMATs have been applied successfully are outlined in Section 9.

1.5 *Units*—The values stated in inch-pound units are to be regarded as the standard. The SI values given in parentheses are for information only.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E127 Practice for Fabrication and Control of Flat Bottomed Hole Ultrasonic Standard Reference Blocks

E428 Practice for Fabrication and Control of Metal, Other than Aluminum, Reference Blocks Used in Ultrasonic Testing (Withdrawn 2019)[3]

E543 Specification for Agencies Performing Nondestructive Testing

E1065 Practice for Evaluating Characteristics of Ultrasonic Search Units

E1316 Terminology for Nondestructive Examinations

2.2 *ASNT Documents:*[4]

SNT-TC-1A Recommended Practice for Personnel Qualifications and Certification in Nondestructive Testing

ANSI/ASNT CP-189 Standard for Qualification and Certification for Nondestructive Testing Personnel

2.3 *Aerospace Industries Association Standard:*[5]

NAS-410 Certification and Qualification of Nondestructive Test Personnel

2.4 *ISO Standard:*[6]

ISO 9712 Non-Destructive Testing: Qualification and Certification of NDT Personnel

3. Terminology

3.1 *Definitions*—Related terminology is defined in Terminology E1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *bulk wave*—an ultrasonic wave, either longitudinal or shear mode, used in nondestructive testing to interrogate the volume of a material.

---

[1] This guide is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.06 on Ultrasonic Method.

Current edition approved June 1, 2022. Published July 2022. Originally approved in 1995. Last previous edition approved in 2017 as E1774 – 17. DOI: 10.1520/E1774-17R22.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

[5] Available from Aerospace Industries Association of America, Inc. (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA 22209-3928, http://www.aia-aerospace.org.

[6] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

***A Summary of Changes section appears at the end of this standard**

3.2.2 *electromagnetic acoustic transducer (EMAT)*—an electromagnetic device for converting electrical energy into acoustical energy in the presence of a magnetic field.

3.2.3 *Lorentz forces*—forces applied to electric currents when placed in a magnetic field. Lorentz forces are perpendicular to the direction of both the magnetic field and the current direction.

3.2.4 *magnetostrictive forces*—forces arising from magnetic domain wall movements within a magnetic material during magnetization, where magnetostrictive materials will undergo a strain in the presence of a magnetic field.

3.2.5 *meander coil*—an EMAT coil consisting of periodic, winding, non-intersecting, and usually evenly-spaced conductors.

3.2.6 *pancake coil (spiral)*—an EMAT coil consisting of spirally-wound, usually evenly-spaced conductors.

4. Significance and Use

4.1 *General*—Ultrasonic testing is a widely used nondestructive method for the examination of a material. The majority of ultrasonic examinations are performed using transducers that directly convert electrical energy into acoustic energy through the use of piezoelectric crystals. This guide describes an alternate technique in which electromagnetic energy is used to produce acoustic energy inside an electrically conductive or ferromagnetic material. EMATs have unique characteristics when compared to conventional piezoelectric ultrasonic search units, making them a significant tool for some ultrasonic examination applications.

4.2 *Principle*—An electromagnetic acoustic transducer (EMAT) generates and receives ultrasonic waves without the need to contact the material in which the acoustic waves are traveling. The use of an EMAT requires that the material to be examined be electrically conductive or ferromagnetic, or both. There are two basic components of an EMAT system, a magnet and a coil. The magnet may be an electromagnet or a permanent magnet, which is used to produce a magnetic field in the material under test. The coil is driven using alternating current at the desired ultrasonic frequency. The coil and AC current also induce a surface magnetic field in the material under test. In the presence of the static magnetic field, the surface current experiences Lorentz forces that produce the desired ultrasonic waves. Upon reception of an ultrasonic wave, the surface of the conductor oscillates in the presence of a magnetic field, thus inducing a voltage in the coil. The transduction process occurs within an electromagnetic skin depth. The EMAT forms the basis for a very reproducible noncontact system for generating and detecting ultrasonic waves.

4.3 *Specific Advantages*—Since an EMAT technique does not have to be in contact with the material under examination, no fluid couplant is required. Important consequences of this include applications to moving objects, in remote or hazardous locations, to objects at elevated temperatures, or to objects with rough surfaces. The EMAT technique is environmentally safe since it does not use potentially polluting or hazardous chemicals. The technique facilitates the rapid scanning of components having complex geometries. EMAT signals are highly reproducible as a consequence of the manner in which the acoustic waves are generated. EMATs can also produce horizontally polarized shear (SH) waves without mode conversion and can accommodate scanning while using SH waves. (Note that in order to produce this wave mode by conventional ultrasonic techniques, either an epoxy or a highly viscous couplant is required. Thus, conventional ultrasonic techniques do not lend themselves easily to scanning when using SH wave modes.) Additionally, EMATs can allow the user to electronically steer shear waves.

4.4 *Specific Limitations*—EMATs have very low efficiency as compared with conventional ultrasonic methods, with insertion losses of 40 dB or more. The EMAT technique can be used only on materials that are electrical conductors or are ferromagnetic. Highly corroded surfaces, especially inner surfaces, may render EMAT unsuitable for use if the surface disturbs the generation of the Lorentz forces. The design of EMAT probes is usually more complex than comparable piezoelectric search units, and are usually relatively large in size. Due to their low efficiency, EMATs usually require more specialized instrumentation for the generation and detection of ultrasonic signals. High transmitting currents, low-noise receivers, and careful electrical matching are imperative in system design. In general, EMAT probes are application-specific, in the same way as are piezoelectric transducers.

5. Basis of Application

5.1 The following items are subject to contractual agreement between the parties using or referencing this guide.

5.2 *Personnel Qualification:*

5.2.1 If specified in the contractual agreement, personnel performing examinations to this standard shall be qualified in accordance with a nationally or internationally recognized NDT personnel qualification practice or standard such as ANSI/ASNT-CP-189, SNT-TC-1A, NAS-410, ISO 9712, or a similar document and certified by the employer or certifying agency, as applicable. The practice or standard used and its applicable revision shall be identified in the contractual agreement between the using parties.

5.3 *Qualification of Nondestructive Agencies*—If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as described in Practice E543. The applicable edition of Practice E543 shall be specified in the contractual agreement.

5.4 *Procedures and Techniques*—The procedures and techniques to be utilized shall be as specified in the contractual agreement.

5.5 *Surface Preparation*—The pre-examination surface preparation criteria shall be as specified in the contractual agreement.

5.6 *Timing of Examination*—The timing of examination shall be as specified in the contractual agreement.

5.7 *Extent of Examination*—The extent of the examination shall be as specified in the contractual agreement.

5.8 *Reporting Criteria/Acceptance Criteria*—Reporting criteria for the examination results shall be in accordance with the contractual agreement. Since acceptance criteria (e.g. for reference radiographs) are not specified in this guide, they shall be stated in the contractual agreement.

5.9 *Reexamination of Repaired/Reworked Items*—Reexamination of repaired/reworked items is not addressed in this guide and if required shall be specified in the contractual agreement.

6. Standardization

6.1 *Reference Standards*—As with conventional piezoelectric ultrasonic examinations, it is imperative that a set of reference samples exhibiting the full range of expected material defect states be acquired or fabricated and consequently examined by the technique to establish sensitivity (see Practices E127 and E428 for descriptions of standard configuration and fabrication).

6.2 *Transducer Characterization*—Many of the conventional contact piezoelectric search unit characterization procedures are generally adaptable to EMAT transducers with appropriate modifications (see Guide E1065 for such transducer characterization procedures). Specific characterization procedures for EMATs are not available and are beyond the scope of this document.

7. Theory (**1-3**)[7]

7.1 *Nonmagnetic Conducting Materials*—The mechanisms responsible for the generation of elastic waves in a conducting material are dependent on the characteristics of that material. The generation of acoustic waves in a nonmagnetic conductive material is a result of the Lorentz force acting on the lattice of the material. In an effort to understand the action of the Lorentz force, one can use the free electron model of solids. According to the free electron model of conductors, the outer valence electrons have been stripped from the atomic lattice, leaving a lattice of positively charged ions in a sea of free electrons. In order to generate elastic waves in a material, a net force must be transmitted to the lattice of the material. If only an electromagnetic field is generated in a conductor (via an eddy current-type coil), the net force on the lattice is zero because the forces on the electrons and ions are equal and opposite. For example:

$$\text{force on electrons} = -qE$$
$$\text{force on ions} = +qE$$

where:

q = electron charge, and
E = electric field vector of EMAT wave.

However, if the same electromagnetic field is generated in the presence of an applied static magnetic field, a net force is transmitted to the lattice and results in the generation of elastic waves. The reason for this net force is the Lorentz force acting on the electrons and ions.

$$\text{Lorentz force} = F_L = qv \times B \qquad (1)$$

where:

v = velocity of electrons, and
B = static magnetic inductor vector.

Since the electrons are free to move and the ions are bound to the lattice, the Lorentz force on the electrons is much greater due to its velocity dependence, and this force is transmitted to the ions in the lattice via the collision process.

7.2 *Magnetic Conducting Materials*—For magnetic conductors, other forces such as magnetostrictive forces, in addition to the Lorentz force, influence ion motion. In magnetic materials, the electromagnetic field can modulate the magnetization in the material to produce periodic magnetostrictive stresses that must be added to the stresses caused by the Lorentz force. The magnetostrictive stresses are complicated and depend on the magnetic domain distribution, which also depends on the strength and direction of the applied static magnetic field. Although the magnetostrictive forces present in magnetic conductors may complicate the theoretical analysis, this additional coupling can be an asset because it can significantly increase the signal strength compared to that obtained by the Lorentz force alone. At high applied magnetic field strengths above the magnetic saturation of the material, the Lorentz force is the only source of acoustic wave generation. The magnetostrictive force dominates at low field strengths, however, and the acoustic energy can be much greater than for corresponding field strengths with only the Lorentz mechanism. Therefore, a careful examination of the relationship at low applied field strengths should be made in order to take full advantage of the magnetostrictive effort in magnetic materials.

7.3 *Wave Modes*—With the proper combination of magnet and coil design, EMATs can produce a longitudinal, shear, Rayleigh, SH-Plate, or Lamb wave mode (**2-4**). The direction of the applied magnetic field, geometry of the coil, and frequency of the electromagnetic field will determine the type of wave mode generated with EMATs.

7.3.1 *Longitudinal Wave Mode*—Fig. 1 illustrates how the direction of the applied static magnetic field in a conductor and the resultant direction of the Lorentz force can produce longitudinal elastic waves. For longitudinal wave generation, the Lorentz force and thus ion displacement is perpendicular to the surface of the conductor. The efficiency of longitudinal wave generation, as compared with other modes excited in ferromagnetic materials, is very low.

7.3.2 *Shear Wave Modes*—Fig. 2 shows how the direction of the applied static magnetic field in a conductor and the resultant direction of the Lorentz force can produce shear elastic waves. For shear wave generation, the Lorentz force and thus ion displacement is parallel to the surface of the conductor. EMATs are also capable of producing shear wave modes with both vertical and horizontal polarizations. The distinction between these two shear wave polarization modes is illustrated in Fig. 3.

7.3.3 *Rayleigh Wave Mode*—In general, for Rayleigh wave generation, the applied static magnetic field will be oriented perpendicular to the surface of the conductor in the same

---

[7] The boldface numbers in parentheses refer to the list of references at the end of this guide.

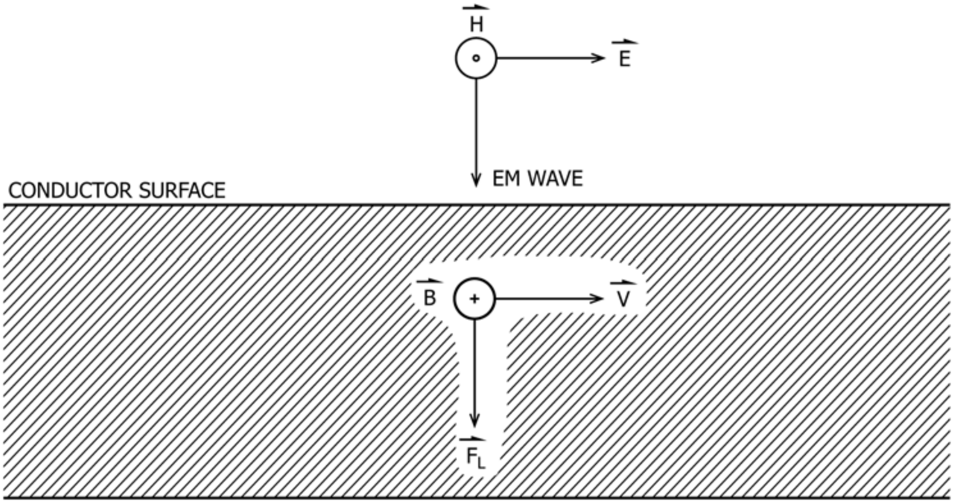

FIG. 1 EMAT Generation of Longitudinal Waves

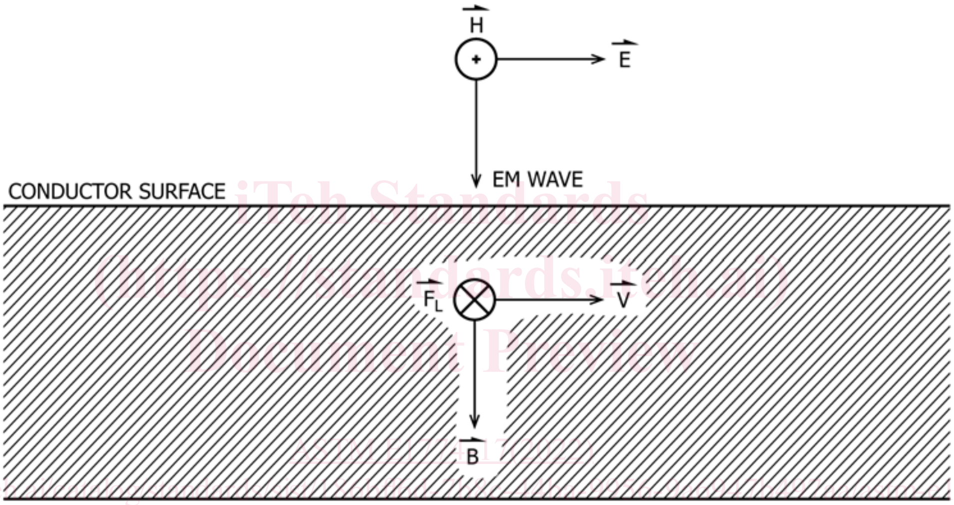

FIG. 2 EMAT Generation of Shear Waves

manner used for shear wave propagation. A meander line or serpentine-type coil is used to provide a tuned frequency EMAT. The frequency of the EMAT is determined by the geometry (that is, line spacing) of the meander lines in the coil. By proper selection of frequency, it is possible to propagate only Rayleigh waves. If the thickness of the material is at least five times the acoustic wavelength that is determined by the frequency and wave velocity, then Rayleigh wave generation is essentially ensured.

7.3.4 *Lamb Wave Modes*—The various Lamb wave modes (symmetric and antisymmetric) can be generated in a manner similar to Rayleigh wave propagation. For Lamb wave production, the tuned frequency of the meander line coil is chosen to give the desired Lamb wave mode and is dependent on the material thickness.

8. System Configuration

8.1 *Transducers*—As in conventional piezoelectric-type ultrasonic examination, there are basically two types of EMATs with respect to beam direction. EMATs can be designed for either straight or angle beam examination. Examples of these two types of transducers are presented in the following sections.

8.1.1 *Straight Beam*—The spiral or pancake coil design is one of the most efficient EMATs for producing a straight ultrasonic beam. The direction of the applied magnetic field is perpendicular to the plane of the spiral coil, as shown in Fig. 4. The magnetic field can be produced by a permanent magnet, an electromagnet, or a pulsed magnet. Assuming that there is no fringing of the magnetic field parallel to the coil, a radially polarized shear wave is produced. Since there is always a small gradient of the field lines parallel to the coil, a small amplitude longitudinal wave will also be present. However, the longitudinal wave component can be held to a minimum by the proper design of the EMAT. The same holds for butterfly coils, placed in a perpendicular magnetic field with spatially alternating magnetic direction for the excitation of linearly-polarized shear waves.

8.1.2 *Angle Beam*—The meander line or serpentine coil EMAT can be designed for angle beam ultrasonic examination.

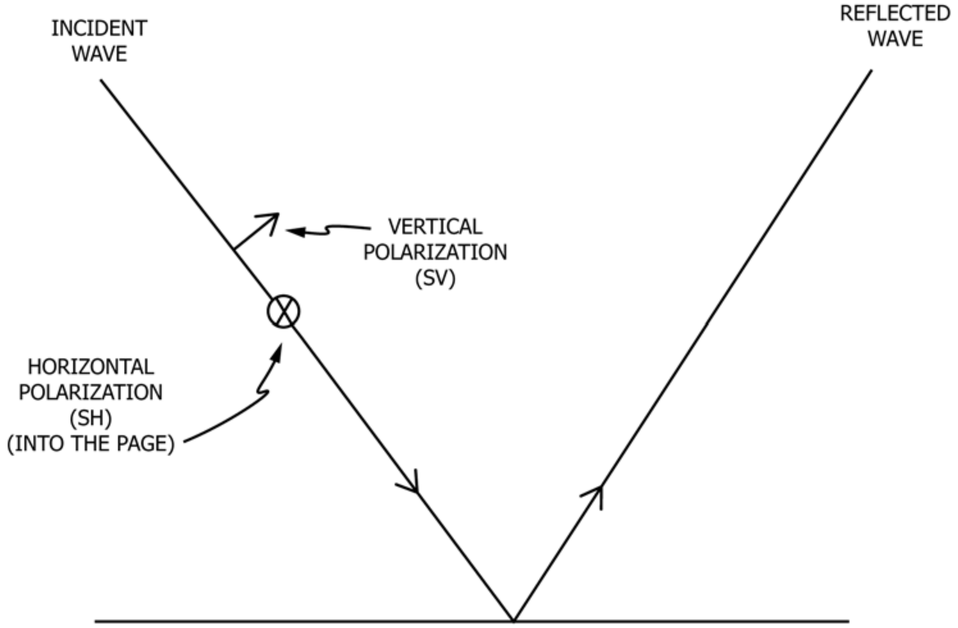

FIG. 3 Illustration of Horizontal and Vertical Polarizations for Shear Waves

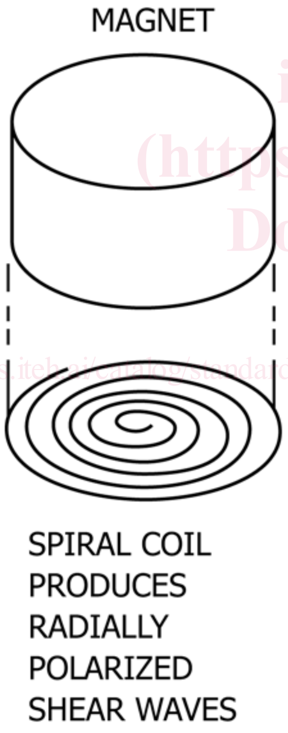

FIG. 4 Diagram of Spiral Coil EMAT

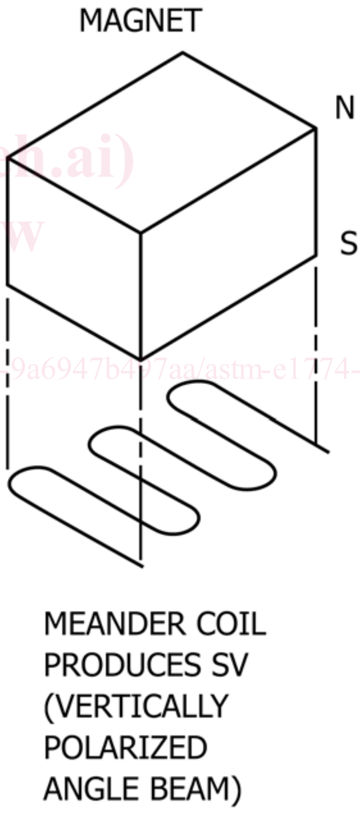

FIG. 5 Diagram of Meander Coil EMAT

The orientation of the applied magnetic field is perpendicular to the plane of the meander coil, as shown in Fig. 5. The geometry of the meander lines is illustrated in Fig. 6. Due to the geometry of the meander lines, periodic surface stresses are generated in the specimen. These stresses produce ultrasonic waves when the following phase matching condition is fulfilled:

$$n\lambda = 2L \tag{2}$$

where:

n = odd integer,
λ = Rayleigh wavelength, and
L = spacing between adjacent coil lines.

Phase matching to bulk waves is achieved when the projection of the wire spacing into the propagation direction of the selected bulk mode is given by