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Standard Guide for
Mutual Inductance Bridge Applications for Wall Thickness Determinations in Boiler Tubing[1]

This standard is issued under the fixed designation E2337/E2337M; 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 describes a procedure for obtaining relative wall thickness indications in ferromagnetic and non-ferromagnetic steels using the mutual inductance bridge method. The procedure is intended for use with instruments capable of inducing two substantially identical magnetic fields and noting the change in inductance resulting from differing amounts of steel. It is used to distinguish acceptable wall thickness conditions from those which could place tubular vessels or piping at risk of bursting under high temperature and pressure conditions.

1.2 This guide is intended to satisfy two general needs for users of industrial Mutual Inductance Bridge (MIB) equipment: *(1)* the need for a tutorial guide addressing the general principles of Mutual Inductance Bridges as they apply to industrial piping; and *(2)* the need for a consistent set of MIB performance parameter definitions, including how these performance parameters relate to MIB system specifications. Potential users and buyers, as well as experienced MIB examiners, will find this guide a useful source of information for determining the suitability of MIB for particular examination problems, for predicting MIB system performance in new situations, and for developing and prescribing new scan procedures.

1.3 This guide does not specify test objects and test procedures for comparing the relative performance of different MIB systems; nor does it treat electromagnetic examination techniques, such as the best selection of scan parameters, the preferred implementation of scan procedures, the analysis of image data to extract wall thickness information, or the establishment of accept/reject criteria for a new object.

1.4 Standard practices and methods are not within the purview of this guide. The reader is advised, however, that examination practices are generally part and application specific, and industrial MIB usage is new enough that in many instances a consensus has not yet emerged. The situation is complicated further by the fact that MIB system hardware and performance capabilities are still undergoing significant evolution and improvement. Consequently, an attempt to address generic examination procedures is eschewed in favor of providing a thorough treatment of the principles by which examination methods can be developed or existing ones revised.

1.5 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

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 and health practices and determine the applicability of regulatory requirements prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1316 Terminology for Nondestructive Examinations

3. Terminology

3.1 *Definitions*—The definitions of terms relating to conventional magnetic examination methods can be found in Terminology E1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *inductance*—the property of an electric circuit or device whereby an electromotive force is created by a change of current in it or in a circuit near it.

3.2.2 *mutual inductance*—the electrical property of circuits that enables a current flowing in one conductor (or coil) to induce a current in a nearby conductor (or coil).

3.2.3 *mutual inductance bridge (MIB)*—a nondestructive examination method, which employs a magnetic induction

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[1] This guide is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.07 on Electromagnetic Method.

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[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.

method for the detection and assessment of variations of wall thickness in tubular vessels. In this procedure, an appropriate magnetic field is first induced into two identical sections of ferromagnetic or non-ferromagnetic tubing through two identical coils, and then a bridge circuit between the two coils is constructed and balanced from a voltage measurement. Although, the two coils are identical, one is designated as the reference coil and is left in place with the other (probe) coil being moved to a section of pipe with unknown thickness. The electrical effect of the tubing is to modify the inductance of the coil used to generate the field, and the resulting voltage reading becomes proportionate to a change in mass of steel in the field. Based on this comparison the section of tubing is judged to be either acceptable or unacceptable.

4. Summary of the Technology

4.1 *Introduction*—A method was needed to rapidly make adequate relative wall thickness measurements for a wide variety of steel piping without any removal of surface contaminants. The Mutual Inductance Bridge (MIB) described here meets these requirements.

4.1.1 The MIB has been used successfully as an applied nondestructive testing tool. This non-destructive examination technique is based on a generic electrical circuit. The MIB is capable of detecting many larger flaws in large, metallic systems with repeating elements with somewhat less than 100 % reliability. However, it uses the system under examination to provide in-situ standardization, eliminating a common problem. It is very robust, portable and safe, making rough handling by unskilled operators acceptable, and it is fast to apply compared to competing techniques. It can, therefore, be useful in detecting non-life-threatening flaws in systems where a substantial but incomplete reduction in failures is beneficial and 100 % accuracy is not required. There are systems in use in industry today where the consequences of in-use failures of loss of life or personal injury. The systems often occur in very large industrial installations where inexpensive components are strictly limited to costly down time. Such failures rarely result in nondestructive examination techniques (eddy-current, dye-penetrant, ultrasound, X-ray and more) that might easily detect nearly 100 % of incipient problems in time to prevent system failures are usually not cost-effective because they are orders of magnitude too slow, use delicate instruments unlikely to survive in many industrial environments, or require very expensive equipment and highly skilled operators. The overall situation can be summarized as follows: It is not cost-effective to perform near-100 %-effective tests for some flaws in some large industrial systems using existing technology, while at the same time, such flaws are nearly 100 % certain to induce very costly failures. The purpose of the MIB is to access the middle ground. The MIB system is substantially, but not 100 % effective in locating relatively large flaws in industrial systems that exhibit spatially repetitive or translationally invariant structures, the simplest example of which is an array of tubes that might be used in a heat exchanger, and for which the example we discuss here is optimized. Note that although the following description uses heat exchangers as a specific example, the MIB is by no means limited to either ferromagnetic steel tubing or heat exchangers, but may be applied to many systems. The measurements are average values taken over the volume of the generated magnetic fields, and should not be considered as point values. The system described here was created to measure the mass variance of identical materials in two identical magnetic fields.

4.1.2 This guide is intended to provide a practical introduction to MIB-based nondestructive examination, highlighting successful applications and outlining failures, limitations, and potential weaknesses. MIB voltage signals are considered from the perspective of flaw detection in 4.2. In 4.2.2, reviews of some of the types of MIB measurements are presented.

4.2 *Operating Principles*—For a satisfactory understanding of the relevant physics behind the MIB, consideration must be given to inductance. Faraday's Law for a coil tells us that the voltage induced in a conductor is given by:

$$V_{induced} = N\, d\Phi/dt$$

where:

V = the amount of induced voltage in volts,
N = the number of turns of wire, and
$d\Phi/dt$ = the rate of change of flux cutting the conductor or coil in webers/second.

In addition, self inductance, usually referred to as simply inductance L, is the property of a circuit whereby a change in a current causes a change in voltage. This is given by:

$$V_L = di/dt$$

where:

V_L = the induced voltage in volts,
L = the value of self inductance in henries, H, and
di/dt = the rate of change in current in amperes per second.

We also need to consider mutual inductance as the electrical property of a circuit enabling a current flowing in one conductor (or coil) to induce a current in a nearby conductor (or coil). This is given by:

$$M = k\sqrt{L_1 L_2}$$

where:

M = the mutual self inductance in henries, H,
k = the coefficient of coupling between the two conductors, and
L_1 and L_2 = represent the values of the two inductances.

Two conductors are said to be coupled when they are arranged so that a changing magnetic field created by one of the coils can induce a current in the other coil or conductor. Finally, a significant physical element underpinning the MIB is the "skin depth" of the current in effective electrically conducting component. The skin depth reflects the exponential decay of magnetic field intensity into the conducting component and is defined by:

$$\delta = \sqrt{2/\omega\mu\sigma}$$

where:

μ = the magnetic permeability,
ω = the angular frequency, and
σ = the electrical conductivity.

This shows that the penetration of the magnetic field into the conducting material is reduced when the frequency, permeability, or conductivity is increased. Since the complex geometry of the materials under examination, such as the webbing on tubes, and the nonlinear dependence of the magnetic permeability on magnetic field intensity also affects the field distribution in the material, the effective skin depth is best found empirically and the skin depth relation is most useful for noting the dependence on the various physical parameters. By using an appropriate frequency, the ac magnetic field can approximately penetrate the wall thickness and the electrical effect of the wall material is to modify the self inductance of the coil that is used to generate the magnetic field. For example, at 60 Hz, the field will fully penetrate a low carbon steel wall of approximately 2.5 mm [0.100 in.]. The change in self inductance *L* is a complex variable that can be expressed in real and imaginary parts (mathematical notation) and which depends on the total volume of metal in the effective region of the coil, including its geometry. For our purposes, it is the sensitivity of *L* to the total volume and geometry of metal in the region of sensitivity of the coil that will enable detection of wall erosion or major voids. Unfortunately, substantial (that is, large enough to indicate replacement at a scheduled maintenance) changes in wall thickness arising from flame erosion or significant internal corrosion might change *L* by only a few percent. To reliably detect a 1 % change in *L* is simple in a laboratory, but impossible in a coal fired power generation boiler. A problem exists from an environment where accurate instruments are subject to rough handling and temperature changes. Another important factor is that the tubes often come from many different lots, including different manufacturers, and so "knowing" a good value of *L* would turn into a bookkeeping nightmare, as the value of *L* for every lot of tubing, and its location in the plant, would need to be tracked. It might, therefore, seem simple to measure a known "good" section of tube at each location, something that can be found reliably, and compare readings of suspect sections. This process still requires very accurate readings, something that must be avoided if the defects a plant operator needs to find are to be detected, and a probable reason that such techniques have not been in use.

4.2.1 *The Bridge Circuit:*

4.2.1.1 There is, however, another approach that eliminates the need for an accurate measurement system. This approach is a "bridge" circuit, where variation in inductance of each of two identical coils reflects differences in the tubing inside the coils, illustrated in Fig. 1. Because the circuit is sensitive only to differences, various external perturbations, disastrous for the direct precision measurement of *L*, affect examination and reference tubes equally, so that the bridge measurement becomes insensitive to these problems. The circuit elements perform the following functions:

(1) Two resistors (R1) and a potentiometer (P1) provide "real" or dissipative balance adjustment so that a very small residual signal is observed when both the reference and probe coils are placed on good tubing.

(2) An additional two resistors (R2) and another potentiometer (P2) provide "reactive" or inductive balance adjustment so that a very small residual signal is observed when both the reference and probe coils are placed on good tubing.

(3) Each coil should be fabricated using several turns of copper wire meeting the specifications of the instrument manufacturer.

(4) Two high-current, low-frequency power transformers are employed. These enable the very low impedance of the coils to be increased 100 fold, thereby greatly reducing the sensitivity of the system to stray magnetic fields and electrical noise. The transformers provide several amperes of ac to coils to ensure adequate excitation of ferromagnetic steel. For stainless steel and other non-ferromagnetic metals, lower excitation may be used, but there is no real advantage to this, since signal/noise ratio could be degraded at low drive levels.

(5) A means of generating an alternating current signal, for example a 120V to 60V 60–400 Hz power transformer is employed.

(6) Remember that the application is focused on power plant boilers, where electricity contains many harmonics, and the use of a sine-wave inverter and storage battery could render the system portable and insensitive to the harmonic content.

4.2.2 *Application Example:*

4.2.2.1 To perform an examination, a reference coil is placed around a tube, or aligned flush with the surface and centered over the joint between two of the water wall tubes. The second or probe coil is placed around or on a similar

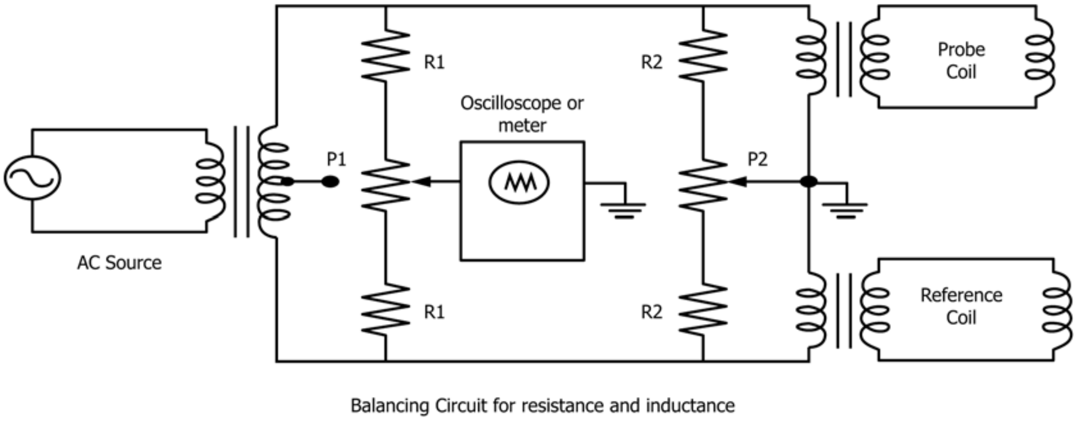
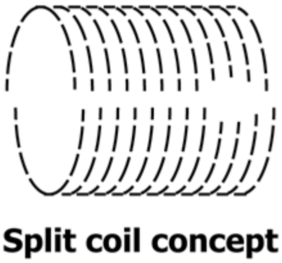


FIG. 1 Generic MIB Circuit

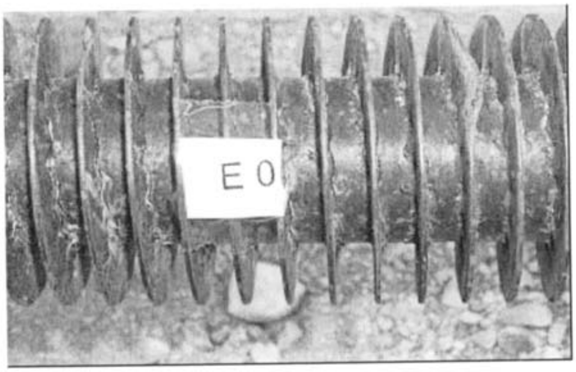
section of pipe and the bridge circuit is balanced. The reference coil is kept in place while the probe coil is moved over sections with unknown properties. It is useful, but not necessary for the probe coil to be on a good section because only differences will be detected, and if, by chance, the probe coil begins on a bad section, then all good sections (presumably most of the system) will provide similar readings to each other, while defective sections will provide different ones. Then, the two potentiometers are easily adjusted by the operator for a minimum signal. In order to place a coil around a tube, it is either necessary to cut the tube from any manifold or header, or conversely fabricate a split coil which can be placed around the tube as is shown in Fig. 2.



NOTE 1—A split coil could be fabricated with bayonet joints so it can be inserted over a heat exchanger tube.

FIG. 2 Split Coil Concept

4.2.2.2 In this illustration, we shall use an example of a spiral heat exchanger tube in a coal fired electric power generation plant. Placing a coil around or adjacent to a tube, produces identical results. The coils are positioned around a "good" section of spiral wound economizer tubing like that shown in Fig. 3 with the corresponding oscilloscope trace in Fig. 4.

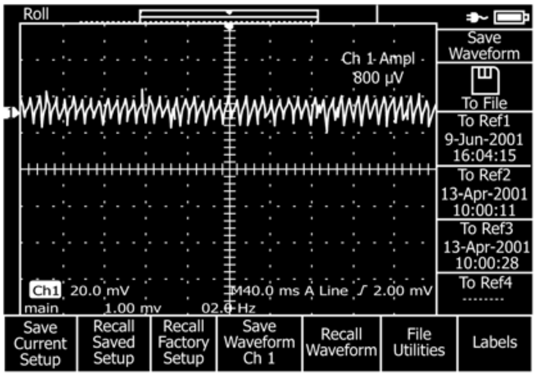


NOTE 1—"Good" section of spiral wound economizer tubing where the edges of the internal cylinder are parallel.

FIG. 3 Good Pipe

4.2.2.3 When about ⅔ of a small section of the wall is ground away, an estimated 6 % of the total wall mass, the test object Fig. 5 and corresponding oscilloscope trace Fig. 6 show that the signal has increased nearly 100 fold to 82 mV.

4.2.2.4 Fig. 5 shows a grinder induced defect, and Fig. 6 the corresponding increase in voltage over the balanced bridge.



NOTE 1—The oscilloscope trace indicating a bridge voltage imbalance of 800 µV.

FIG. 4 800 µV Signal

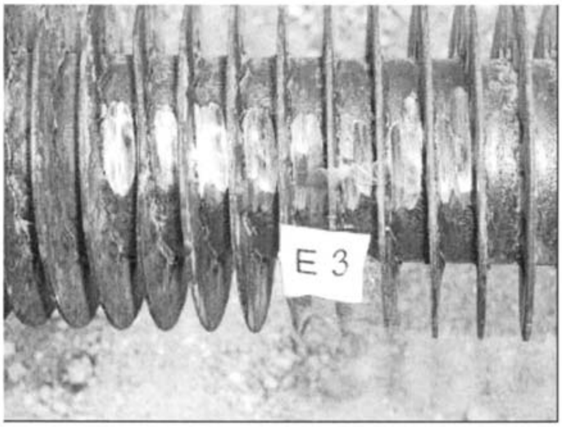


FIG. 5 Grinder Defect

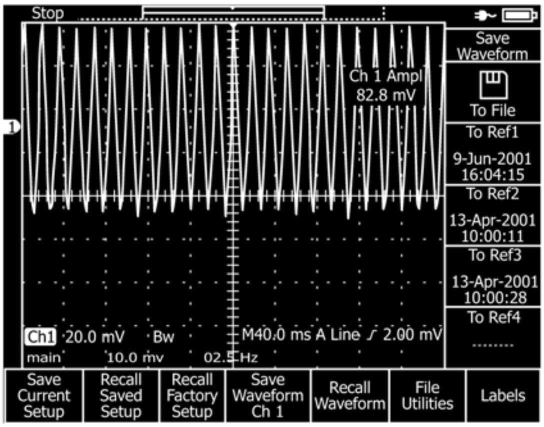


FIG. 6 82 mV Signal

4.2.2.5 Conversely, when the probe coil is passed over a region with the erosion pattern shown in Fig. 7, the corresponding voltage reading is 102 mV Fig. 8. Note the "sawtooth" wear pattern of erosion between each pair of fins.

4.2.3 *Precautions:*

4.2.3.1 The MIB signal is directly proportional to the mass of identical magnetic material in the respective fields. If neither wall erosion nor reducing atmosphere fireside corrosion mechanisms are the primary problem, the MIB method will

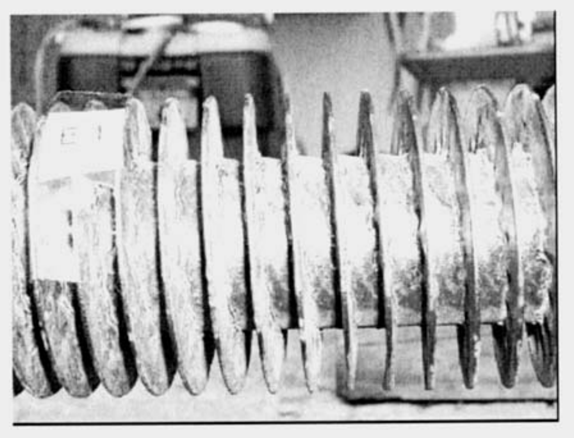


FIG. 7 Sawtooth Wear Pattern

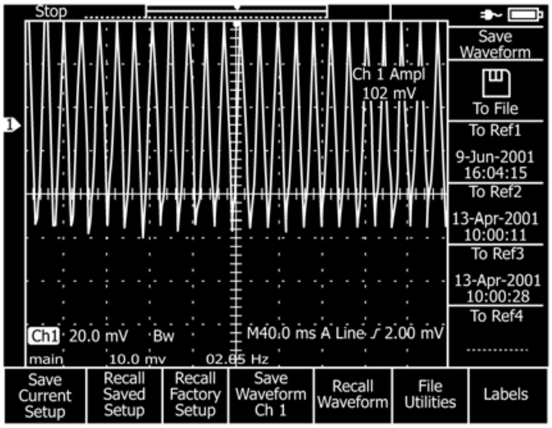


FIG. 8 102 mV Signal

have little benefit. Specifically, cracks and pits will most likely not be detected by this method unless the defects are very large. Other limitations may exist due to physical access restrictions, and if vast composition differences are evident in the same wall section, it may be difficult to discern a variation in wall thickness from a material change. During set up and bridge balance, the measurements should be correlated to other meaningful measurement standards, like ultrasonic examination. Finally, it is recommended that the reference and probe coils be separated by at least one coil diameter to prevent magnetic field interference.

5. Significance and Use

5.1 The primary advantage of a mutual inductance bridge is its ability to make wall thickness measurements quickly. Since surface contaminants (ash and slag) are not ferromagnetic, they do not interfere with the electromagnetic measurement. As a result, the surface requires no preparation. Since a wide variety of steels are employed in a boiler, an in-situ standardization using the material under measurement as the reference is adequate.

6. Apparatus

6.1 A generic schematic apparatus for constructing a MIB circuit is shown in Fig. 1.

7. Keywords

7.1 bridge circuit; inductance measurement; mutual inductance bridge; wall thickness

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