EMAT Based Ultrasonic System for Determination of Thickness Variation in Metallic Samples

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ABSTRACT

Thickness measurement is an important primary measurement parameter. It itself and from the various derived parameters, provides valuable information in testing and process industries. Although numerous techniques are available for thickness measurement which provide very good results for transparent material and when both sides are accessible, but these methods have limitations in case of opaque material and when only one side is accessible. A new EMAT based non contact technique is reported in this paper which is capable of measuring thickness variation even in opaque material and if only one side is accessible. Using EMAT it was possible to measure the thickness of a material in the order of a few nanometers. This was achievable by the facility developed at NPL, India to measure ultrasonic Time of Flight (TOF) to an accuracy of nanoseconds with deviation of 300 picoseconds. An experiment was done using EMAT to measure the variation in thickness due to stamped notch in an aluminum block having thickness of 25 mm. EMAT system was able to measure considerable variation in the thickness due to notch. An experiment was also done on circular metallic pipe to determine the variation in inner diameter by measuring wall thickness. Excellent result was obtained with greater precision. This better precision is achieved because of Beam Width to Reflector ratio being close to unity. In case of flat plates this ratio is much greater than unity. To reduce this ratio to unity even in case of flat plates several samples were used in conjunction with EMAT and experiments were again performed on the above mentioned aluminum block to determine the variation in thickness due to notch.

Present paper reports the results obtained in determining the variation of thickness in case of aluminum block with notch and circular metallic pipe using EMAT based ultrasonic system.

Introduction

In terms of the man-made environment, industry must contend with thickness that varies from meters for construction projects, to millimeters in assembly lines, to micrometers and nanometers for the solid-state, optical, and coatings industries. Perhaps the most familiar way of measuring thickness is by mechanical means, such as by ruler or caliper. Other means are sometimes called for, either because both sides of an object are not accessible, the dimension is either too big or too small for calipers, the object is too fragile, too hot, or too cold for direct contact, or the object is in motion on an assembly line or it may not even be a solid. Thickness may also be a function of position, as either the object may have originally been made with non-uniform thickness, deliberately or not, or the thickness may have become non-uniform with time due either to corrosion, cracking, or some other deterioration. The thickness may also be changing with time due to deliberate growth or etching, as example for thin films. Thus it follows that, in more general terms, measuring thickness might require measuring the topography or height profile of two surfaces and taking the difference. Alternatively, the measurement technique may produce a reading directly related to the difference. The fundamental tool for measuring thickness is the line-graduated instrument [1, 2]. It is the only mechanical means to make direct measurements. Graduated spacing that represents known distances is used as direct comparisons to the unknown distance. An object of fixed geometry (length, tapered bore, thread, etc.) is compared to a test piece typically for part inspection. A Linear Variable Differential Transformer (LVDT), based electronic thickness gaging systems serves as a replacement for a lined ruler or micrometer, incorporating an electrical readout. It utilizes multiple toroidal transformers to sense axial displacement of an iron core that is attached to a measuring contact, either directly or by another joint (such as a lever). The displacement has a direct correlation to the distance that other electronics display. With the help of Pneumatic Gaging tolerances as small as 50nm can be measured. Pneumatic gages have pressurized air exiting gage orifices. The air velocity differential or back pressure is a function of gage separation and the part.

In optical methods, thickness determination can be classified based on the principles of focusing, shadowing and comparing. This includes microscopes, which can determine thickness either by comparison with a known reference, or by focusing on the front and rear surfaces of a sample, noting the difference in focus position. Comparators project onto a screen what might be noted through a microscope. Laser calipers retrieve dimensions by measuring the shadowing of a laser beam.

Capacitive Gaging, Inductive Gaging (Eddy Current Sensing), Magnetic Induction and Hall effect Gaging are extensively studied under magnetic and electrical methods which comparatively provide less precise values of thickness. Capacitive gaging is realized by inserting a nonmetallic material into a known electric field. Knowing the gage sensor area and the material's dielectric constant, the thickness can be determined. Submicron thickness levels can be achieved. Principle involved in Inductive Gaging (Eddy Current Sensing) is that ac currents in a coil induce eddy currents in a nearby conducting plate [3, 4, 10]. These eddy currents can be sensed by a pickup coil, which may be the exciting coil or a second coil. This technique is appropriate for nonferrous metals, and is especially sensitive to thickness variations due to flaws such as cracks or corrosion. The range of this technique would be about 1mm. The magnetic induction technique is also used to measure coating thickness such as a nonmagnetic coating on a ferromagnetic substrate. The nonmagnetic coating creates a gap (lift-off) between the ferromagnetic substrate and a probe. One way to measure the gap and thereby the thickness is by measuring the force required to pull away a magnetic probe. Another technique would be to magnetically couple the ferromagnetic substrate to a transformer core, with a gap between the substrate and the core. This technique would have a range of about 4 mm. Hall Effect Gage sensor measures the thickness of nonferrous materials with 1% accuracy by sandwiching the material being measured between a magnetic probe on one side and a small target steel ball on the other side [5]. It measures up to a maximum of 10mm.

A few methods can be classified based on the measurement principle involved namely Far-Field/Time-of-Flight which comprises Ultrasound, Radar and Lidar based systems, Far-Field/Resonance which constitutes Ultrasound, Interferometry and Ellipsometry [3,7,8,11] and Far-Field/Absorption, Scattering, Emission which comprises Beta, Gamma, X-Ray, Infrared systems [9].

Using the conventional sonar principles, and today's microprocessor technology, high-frequency (1-20MHz) ultrasound waves can be used to measure thickness by sending pulsed sound waves through a material and measuring the transit time of the re?ected signal [4, 6]. Knowing the sound velocity of the material, thickness from 0.5mm to 250mm can be measured, often as ?ne as 25fim (using conventional Piezoelectric materials). Media include metal, glass, ceramic, liquid, rubber, fiber glass, plastic, and concrete. Ultrasound can also be used to measure living tissues, as often done in the agricultural and medical fields. Ultrasonic thickness determination has expanded to include multidimensional echolocation applications, such as imagery and acoustic microscopes that can resolve in the submicron level.

As is common with the most of the above mentioned techniques, estimating the thickness requires knowledge of some other property of the material to be measured. In the present case of thickness measurement using ultrasonic systems involving the principle of time of flight one should have precise value of ultrasonic velocity in the material being tested. But if the application interest is restricted to measuring variation of thickness rather than absolute thickness then only the precise measurement of Ultrasonic TOF will suffice to detect variations up to micron level. Present paper describes the Electromagnetic Acoustic Transducer based non contact and non destructive ultrasonic system in measuring variation of thickness in metallic samples up to a level of 1 micron. This technique helps to measure the thickness variation even if the other surface is not accessible and requires no surface preparation.

ElectroMagnetic Acoustic Transducer (EMAT) System at NPL:

Electromagnetic Acoustic Transducers (EMATs) are emerging as a mainstream Non-Destructive Evaluation (NDE) technique. EMATs are electrical devices that can transmit and receive ultrasonic waves in an electrically conducting material, without contacting the material being inspected. EMATs offer several distinct advantages over traditional piezoelectric transducers for many inspection applications requiring novel solutions. These advantages include: operation without a coupling fluid, non-contact operation, high temperature operation, and the ability to utilize shear horizontal (SH) waves. EMATs are also ideally suited for launching and receiving Raleigh waves, Lamb waves, and shear horizontal (SH) plate waves. For bulk wave Lorentz force, EMATs operating condition is such that the ultrasound wavelength should be much longer than the electromagnetic skin depth.

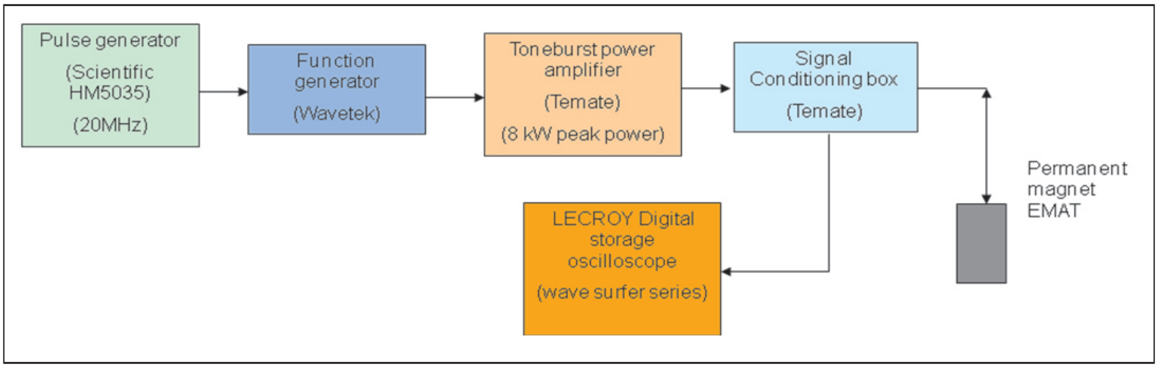

Fig. 1: Block diagram of the EMAT system

Fig. 2: Photograph of EMAT system at NPL

EMATs are the devices that operate on the process of electromagnetic transduction of ultrasonic waves [12]. It is the process of inducing ultrasonic waves in a solid material with the help of an electrically driven coil in the presence of magnetic field. Figure 3 shows a diagram of basic electromagnetic acoustic transducer.

Working principle of EMATs is based upon Lorentz force mechanism and Magnetostriction principle. Considering the physics behind Lorentz force, when a coil of wire placed near the surface of an electrically conducting object is driven by an alternating current at the desired ultrasonic frequency, it produces a time varying magnetic field which in turn induces eddy currents in the material under test. If a static magnetic field is present, the interaction of these eddy currents with the static magnetic field results in a magnetic volume force whose direction and intensity is determined by the vector equation F=J x B, Where F = Lorentz force, B= magnetic field induction, H= magnetic field, J= induced eddy current. This magnetic volume force is called the Lorentz force and this force results in the generation of a wave that propagates within the specimen. When the wave passes the region of the receiving EMAT, local eddy currents are induced in the conductive material, thus resulting in a time varying magnetic field which induces voltage in the coil by Faraday's law.

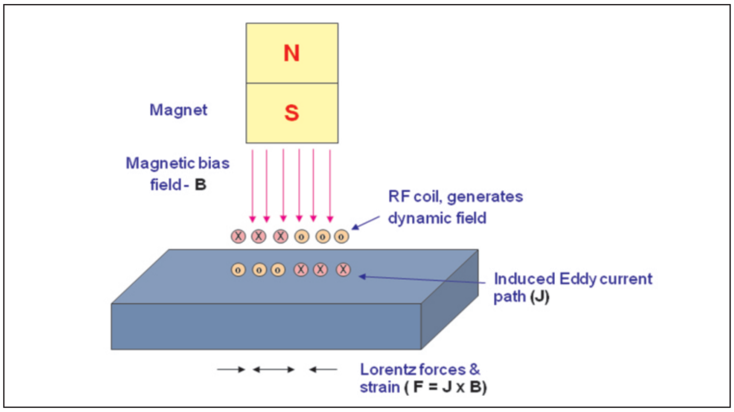

Fig. 3: Schematic diagram of a Basic Electromagnetic Acoustic Transducer (EMAT)

Case Studies for Thickness Variation Measurement

Case I: Thickness Variation Measurement due to Notch on a metallic block.

As discussed earlier, the use of EMAT for generation and reception of ultrasonic waves does not require any kind of couplant since the waves are directly generated inside the material. This advantage of EMAT system primarily eradicates the possibility of errors in Time Of Flight measurement. Apart from this, other sources of error in TOF measurement have to properly identified and addressed so that deviation in TOF can be minimized to the maximum possible extent. Further, such an efficient Ultrasonic system can be employed for precise measurement of thickness of metallic samples compared to other methods of thickness measurement as described in introduction.

Deviations in ultrasonic TOF measurement are mostly caused due to the lack of proper signal processing tools that can be employed on ultrasonic signal. LabVIEW which is an excellent programming tool provides many functions which can be used to efficiently process the signal. At NPL, we have also employed LabVIEW and developed a user interface which refines the signal, applies peak detection algorithm to the echoes and calculates Time of Flight with a precision less than 300 picoseconds. Complete details regarding the development of TOF measurement technique using LabVIEW are presented elsewhere (13, 14). Fig.4 Shows the Front panel of the user interface developed to measure fundamental quantities of ultrasonics namely Time of Flight and Velocity.

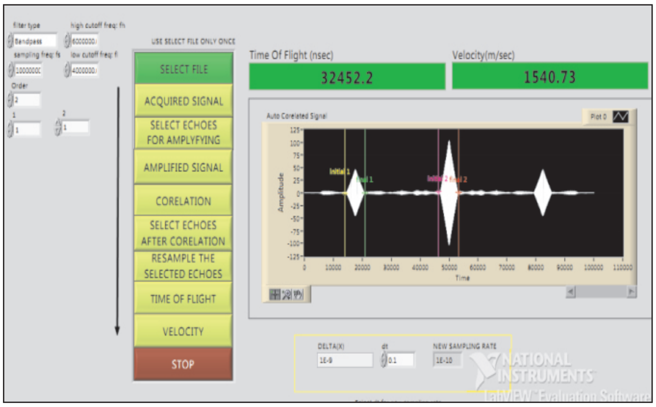

Fig. 4: Snapshot of program developed at NPL for Tone burst excitation of transducer

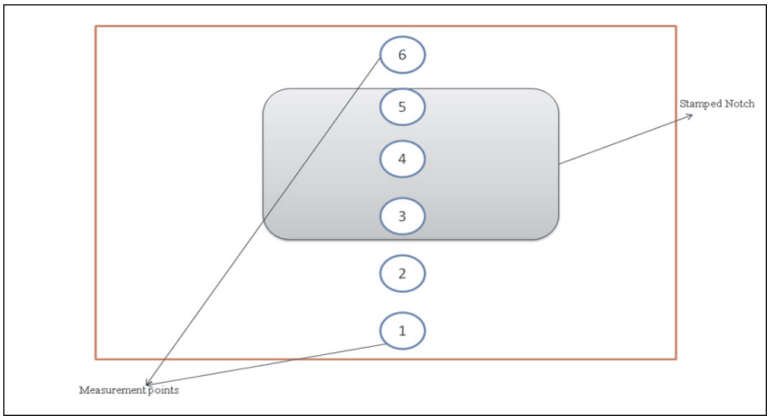

Fig. 5: Schematic of the metallic block of thickness 25mm with stamped notch

Improvement of precision and accuracy in TOF measurement proportionally improves the precision and accuracy in ultrasonic thickness gauging. This EMAT based system has been applied for determination of fine variation in thickness on a metallic block due to stamped notch. A prime advantage of Ultrasonic system in such applications is that variations in thickness can be determined even if the surface on which the notch is present is inaccessible. Figure 5 shows the schematic of the metallic block of thickness 25mm on which stamped notch is present along with the measurement points. The TOF values measured at these points are tabulated in Table I.

Case II: Variation in Inner diameter by measuring wall thickness of a metallic pipe.

Further this system has been applied to find the variation in inner diameter of a metallic pipe. Fig. 6 shows the cross section view of the metallic pipe. The circumference of the pipe is divided into six parts (hexagon) and Fig.7 shows the values of inner diameter as provided by the

Results & Discussions

Table 1: Set of TOF readings made on a metallic block with stamped notch

S.No.	TOF(nanoseconds)
1.	16067.2
2.	16067.2
3.	16064.0
4.	16065.6
5.	16065.6
6.	16067.2
7.	2999.1
-	-
-	-
-	-

Table 2: Set of TOF readings made on a metallic pipe employing EMAT system.

S.No.	TOF (nanosecond)
1.	2999.08
2.	2999.18
3.	2999.12
4.	2999.15
5.	2999.09
6.	2999.14
7.	2999.17
8.	2999.13
AVG	2999.133
STD.DEV	0.035355

From Table I, it can be inferred that due to notch on the metallic block. TOF varies from 1.6 nanoseconds to 3.2 nanoseconds. This corresponds to 2.5 to 5µm variation in thickness due to notch. From Table II, it can be inferred that the precision in TOF measurements improves by factor of 10 due to BWR ratio being close to unity but execution of beam reduction method on metallic block with stamped notch hasn't improved the sensitivity in determining the variation in thickness. The measured change in time of flights remained exactly same as stated before. Below given figures represent the measured variation in inner diameter of the metallic pipe discussed in case study II.

Conclusions

A non contact high precise EMAT based ultrasonic system in conjunction with LabVIEW which can be employed in thickness measurement of metallic samples is presented in this paper. A parameter which further improves the precision in TOF measurement namely Beam Width to Reflector (BWR) ratio had been introduced. An easy way of reducing beam width by employing thin aluminum foils over the face of EMAT coil opens up further scope of research. One such application is residual stress measurement using EMAT. Generally in order to measure the residual stress employment of two SH transducers with different polarizations are required. But with the help of beam width reduction technique a single spiral EMAT coil which generates radially polarized shear waves is expected to be sufficiently enough for producing two differently polarized ultrasonic shear waves. More importantly a great improvement can be noted in the minimum thickness variation measurement over conventional ultrasonic system depicted in literature, by simultaneously providing many other advantages over other thickness gauging techniques.

References

1. R. E. Green (ed.), Machinery's Handbook, 24th ed., New York: Industrial Press, 1992.
2. F. T. Farago and M. A. Curtis, Handbook of Dimensional Measurement, 3rd ed., New York: Industrial Press, 1994.
3. R. C. McMaster, P. McIntire, and M. L. Mester (eds.), Nondestructive Testing Handbook, Vol.4,2nd ed., American Society for Nondestructive Testing, 1986.
4. D. E. Bray and D. McBride, Nondestructive Testing Techniques, New York: John Wiley & Sons, 1992.
5. M. Giannini and A. deChiara, Wall Thickness Gaging in the Blow Mold Industry, distributed by Panametrics.
6. A.S. Birks, R. E. Green, and P. McIntire (eds.), Nondestructive Testing Handbook, Vol. 7, 2nd ed., American Society for Nondestructive Testing, 1991.
7. D. Malacara, Optical Shop Testing, New York: John Wiley & Sons, 1978.
8. J.A. Woollam and P. G. Snyder, Variable Angle Spectroscopic Ellipsometry, VASE, distributed by J.A. Woollam Co.
9. H. H. Behncke, Coating thickness measurement by the X-ray ?uorescence method, Metal Finishing, May, 33-39, 1984
10. J. KrÆl, R. Smid, H. M. Geirnhas Ramos, A. Lopes Ribeiro, Thickness Measurement Using Transient Eddy Current Techniques, 978-1-4244-7935-1/11'2011 IEEE
11. Y. Pavan Kumar and Sanjib Chatterjee, Thickness measurement of transparent glass plates using a lateral shearing cyclic path optical configuration setup and polarization phase shifting Interferometry, APPLIED OPTICS. 49, No. 33 / 20 November 2010.
12. H. Ogi, "Field dependence of coupling efficiency between electromagnetic field and ultrasonic bulk waves," Journal of Applied Physics, 82(1997)3940-3949, 1997.
13. R. Sandeep Kumar, Yudhisther Kumar, Reeta Gupta, Deepa Joshi, Ashok Kumar "Ultrasonic method of measurement of wall thickness variation in a metallic pipe-a case study," National Symposium on Acoustics, 2011
14. R. Sandeep Kumar and Deepa Joshi "LabVIEW based novel applications of ultrasonics in science of measurement," VI MANTRA 2011 by National Instruments.