EMAT EVALUATION OF THIN CONDUCTING SHEETS

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Summary At present a non-destructive testing of conducting materials becomes very important one in connection with monitoring and control of strategic technical facilities, e.g. nuclear power plants. There are more methods of material testing and evaluation and every of them has its advantages and disadvantages. Recently the electromagnetic methods are in increasing interest. There are many ways of conducting material testing. One of them often used utilises investigation of eddy currents induced in the surface layer by means of a proper coil. The arrangement is very simple and inexpensive but it offers only local information on cracks and other inhomogeneities in the thin surface layer. On the other hand there exist a method based on an electromagnetic – acoustic transducer (EMAT), which is able to generate and detect acoustic wave in a conducting body in a contact-less way. The present paper deals with a survey of EMATs for investigation of thin metallic layers by means of Lamb waves. The new design of generation coil is presented.

Keywords: Ultrasound, EMAT, electromagnetic generation of ultrasound, non-destructive testing, ultrasonic defectoscopy.

1. INTRODUCTION

There are still sophisticated and expensive industrial technical facilities, which desire developed procedures of their working reliability, safety and incorruptness monitoring and testing. Discovering of sources of potential malfunctions can save lots of money and some times also human lives. The material testing attracts permanently increasing interest of industry. A special interest is devoted to the non-destructive methods of continual monitoring, which offers a possibility to evaluate permanently the state of industrial facilities like e.g. nuclear power plants.

An increasing attention is devoted to methods based on investigation of electromagnetic or acoustic fields and waves. Ultrasonic defectoscopy represents a known principle, but the attention is devoted to develop new and more efficient electro-acoustic transducers. Many electromagnetic methods are based on the utilization of measurement of electromagnetic field generated or modified by means of eddy currents induced in the surface layer of conducting bodies. Methods of eddy current testing (ECT) are widely used for surface cracks and other damages detection. Disadvantage of ECT consists in a local application and low depth of sensitivity range due to the skin effect. New achievements in this field have been described in many papers, e.g. [1], [2].

On the other hand, ultrasonic methods are very effective in a whole body or of its substantial part to investigate and to detect deep inhomogeneities. Disadvantage of ultrasonic methods consists in the necessity of acoustical coupling of an ultrasonic transducer with a body surface. For this reason, contact-less methods of ultrasound generation and detection are in a centre of attention. One of the principles discussed in these relations is direct electromagnetic generation and detection of ultrasound in conducting bodies. Physical principles of the effect have been widely discussed and published in the past, e.g. [3], [4]. The present attention is devoted to special transducers development. The efficiency of power conversion is very low and it should be a little increased by means of proper transducer optimization. Another complication consists in necessity of utilization of a strong constant magnetic field. It is realized by special permanent magnets or electromagnets.

The present paper deals with different kind of EMAT (electromagnetic – acoustic transducers) in a view of their utilization in the NDT (non-destructive testing). Both bulk and the surface wave will be described and discussed.

2. THEORY

Principle of non-contact electromagnetic generation and detection of acoustic waves in conducting matter is based on the interaction of the electromagnetic wave with an electron gas and ionic lattice of the electrodynamic structure of the matter.

One possibility consists in interaction process under a constant magnetic field. The generating mechanism can be explained as the result of the action of magnetic force on the eddy currents, induced in the surface layer by means of the incident electromagnetic wave. Using the kinetic theory of electron gas in a magnetic field we obtain the expression for the ionic structure displacement, see e.g. [3], [4]. In case of the magnetic field B_c normal to the body surface we obtain the transverse displacement, generating the transverse acoustic wave in z – direction normal to the surface of the sample

$$\xi(z,t) = i\,\frac{2B_c\,H_0}{\omega\rho s_t}\,e^{-i\left(\frac{\omega}{s_t}z-\omega t\right)},$$

where H_0 is magnetic intensity of the electro-magnetic wave at the surface, ρ is the mass density, s_t shear acoustic wave velocity and ω angular frequency. The acoustic excitation polarized perpendicularly to the polarization of the incident electromagnetic wave.

Together with the acoustic wave the accompanying electromagnetic excitation is generated as well. Its electric intensity is expressed as

$$E(z,t) = i\omega B_c \ \ \xi(z,t)$$

$$E(z,t) = \frac{2B_c^2 H_0}{\rho s_t} e^{-\frac{\omega}{s_t} z} e^{i\omega t}.$$

This wave is irradiated from the sample and should be detected by means of an external detector.

On the other hand the acoustic excitation is possible without any external magnetic field. It should be interpreted as the result of a direct action of the incident electromagnetic wave on the induced eddy current. The generated acoustic excitation normal to the surface of the sample is given by

$$\xi_2(z,t) = i \ \frac{\mu H_0^2}{\omega \rho s_t} e^{-i\left(\frac{2\omega}{s_t} - 2\omega t\right)}$$

$$E_2(z,t) = \frac{\mu H_0^2 B_c}{\rho s_t} e^{-i\left(\frac{2\omega}{s_t} - 2\omega t\right)}.$$

In the case of the incident harmonic electromagnetic wave with a frequencyω, the acoustic excitation has a frequency 2ω. We can see that the second-harmonic ultrasound generation is takes place even without constant magnetic field but the accompanying electromagnetic mode is excited only in presence of external magnetic field.

The theory explains the mechanism of generation of ultrasound by means of the incident electromagnetic wave and on the other hand the mechanism of excitation of the accompanying electromagnetic field, which allows detecting the motion of the ionic structure.

3. MODES OF EXCITED WAVES

In practice the exciting electromagnetic wave is realized by means of proper coil. Similar coil or the same one is used for the inverse effect of electromagnetic detection of the acoustic wave. This exciting/detecting coil together with the source of the constant magnetic field represents the electromagnetic – acoustic transducer (EMAT). Different possibilities of utilization of EMAT depend on the mode of the generated acoustic wave. The deep inhomogeneities of the material are usually investigated by means of bulk waves with longitudinal or shear polarization. The surface inhomogeneities are usually investigated by means of surface waves – Rayleigh waves in case of bulky samples, Lamb waves in case of thin sheets. The generated acoustic mode depends on a shape of the generating/detecting coil supplied by an alternating or pulse electric current.

The generating and detecting process can be interpreted by means of the interaction between the coil winding and the induced eddy currents. The time-dependent force exerting on the electrons of the eddy current is transferred to the ionic lattice by means the electron-ion collisions and represent the mechanism of acoustic wave generation.

In the Fig. 1 we can see the origin of the magnetic force, which excites the mechanical vibrations of the system. The current I of the coil winding induces eddy current in the conducting substrate, which is the mirror image of the original current. Fig. 1 (a) and (b) explain a mechanism of excitation of the lattice vibrations, which follow the time dependence of the current I, due to the magnetic force exerting on the eddy currents in a constant magnetic field of two different orientations. In case of harmonic current the vibration represent the 1-st harmonic one. The figure

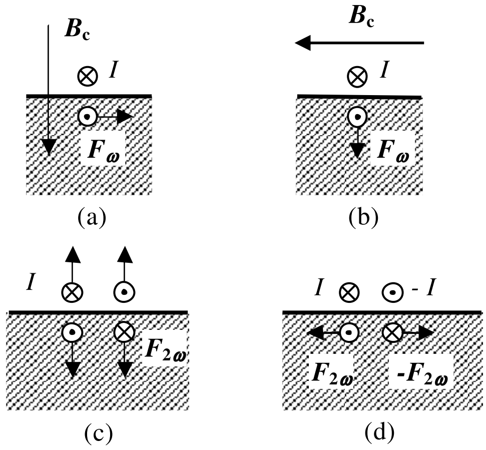

Fig. 1. EMAT excitation.

explains a polarization of the excited vibrations, (Fig. 1 (a), shear excitation parallel to the surface, Fig. 1 (b), longitudinal excitation perpendicular to the surface). The Figs. 1 (c) and (d) explain the excitation of vibrations, which follow time-dependence of the square of the current I^2. In case of harmonic current I the vibrations represent the 2-nd harmonic excitation. In the first case we observe the force between the wire and its mirror image eddy current. The excitation is polarized normally to the surface. In the second case we see the interaction between two neighbouring lines of the eddy current. The excitation is polarized parallel to the surface. In case of currents opposite orientation the force is repulsive; in case of the same orientation the force is attractive.

The Fig. 2 illustrates a principle of electromagnetic detection of an acoustic wave. Under normal conditions the ionic movement is totally screened by electron gas, so that the ionic lattice movement does not cause measurable modulation of the resulting electric charge. In presence of an external magnetic field the screening effect is reduced by the Lorentz force and the resulting charge distribution is a source of an electric field, which can be detected by an adjacent detecting coil. The detectable charge modulation directed along the surface can be reached by means of proper orientation of the constant magnetic field. Detection

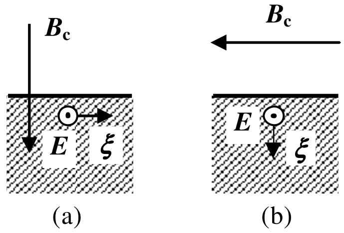

Fig. 2. EMAT detection.

of an ionic movement parallel to the surface needs the external magnetic field normally oriented to the surface, whereas the movement normal to the surface can be detected in presence of the external magnetic field parallel to the surface. The electromagnetic detection of ultrasound in conducting body without presence of the external magnetic field is not possible.

Special arrangement of the exciting coil gives a possibility to generate various modes of the acoustic waves, Fig. 3.

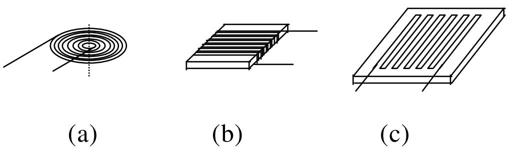

Fig. 3. Typical shapes of generating coils.

Generating/detecting coils for bulk shear or longitudinal waves are most general. The flat spiral coils, Fig. 3(a) are relatively efficient but the ultrasonic beam is quite complex. The advantage of this arrangement consists in the fact that the entire area of the coil generates actively the ultrasonic beam. Another shape of the generating/detecting coil represents the rectangular coil. There are two possibilities. One of them is the rectangular solenoid-like coil, Fig. 3(b), the other is the flat coil with a screened part of its area [5]. This transducer has lower effectiveness but it produces well defined profile of the linearly polarized ultrasonic beam. The meander coil, Fig. 3(c), is suitable for surface acoustic waves generation in presence of constant magnetic field. This kind of transducer works in a resonant regime, which means that the periodicity of the structure must correspond to the wavelength of the surface acoustic wave. In case of proper higher period of the meander structure the transducer generates/detects the bulk wave propagating in an acute angle to the surface of the sample and this angle can be changed by means of the change of frequency of the supplying RF current, see e.g. [6], [7]. Meander transducer for Lamb wave generation and detection is described in [8].

Special attention is devoted to thin conducting sheet testing by means of 2-nd harmonic Lamb wave generation without a constant magnetic field. In this case effect of the constant magnetic field is substituted by effect of the alternating magnetic field produced directly by a winding of the coil or by neighbouring eddy current. The high supplying RF current produces usually stronger magnetic field than that of used permanent magnet or electromagnet of EMAT. Generation of acoustic wave without any constant magnetic field is illustrated in Figs. 1(c, d). In the first case the force normal to the surface is always attractive irrespective of orientation of the current in the coil winding (parallel – Fig. 3(a, b) or anti-parallel – Fig. 3(c)), so that it gives a possibility to generate longitudinally polarized bulk wave. This arrangement is not suitable for surface waves generation. In case of meander coil the neighbouring current have an opposite direction so that the mutual force of neighbouring eddy currents are repulsive, Fig. 1(d). In case of meander coil the force exerting on one current from both neighbouring ones is eliminated, so that this mechanism does not generate both bulk and the surface acoustic wave. The only exception represents a meander coil with only one period. The mentioned problems with generation of surface acoustic waves without any constant magnetic field have been described in [9]. One possibility how to avoid the compensation of the force along the surface consists in utilization of the generation coil with only one period of the meander. This kind of Lamb waves generation has been described in [10].

We have solved the problem of excitation of surface wave due to forces oriented along the surface of the sample by means of specially shaped “double meander coil”, Fig. 4. In case of the same current in both parallel windings the mutual magnetic force exerting on the mirror eddy currents in the sample has uncompensated period character along the surface of the sample. This mechanism is efficient for surface

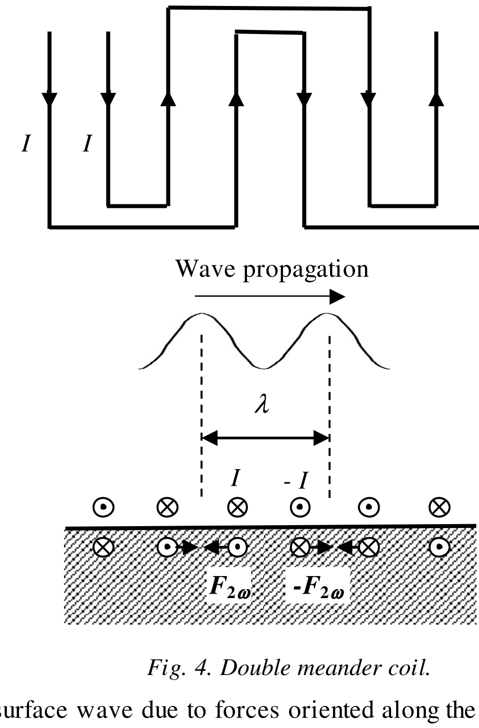

Fig. 4. Double meander coil.

waves generation. The bulk shear mode is suppressed in this case but the longitudinal mode is generated due to the mechanism described in Fig. 1(c). Due to this effect this kind of transducer is not suitable for Rayleigh wave generation in bulky samples. In this case the 1-st harmonic generation by means of a usual meander is more suitable. The described double meander coil is useful for generation of acoustic waves in thin sheets, depth of which is less than an acoustic wave-length. The described method is effective especially in case of generation of Lamb waves, which propagate through the entire cross-section of the sheet. The transducer shape supports mainly the fast S_0 (symmetric) mode of the Lamb wave.

4. RESULTS

We have tested the new type of transducer. The area of the transducer was 12 x 10 mm^2 with 6 periods of windings. It was tested on the Aluminium foil 0.25 mm thick. Receiver was the EMAT with usual meander coil designed for 2-nd harmonic detection. RF current pulses 10 A with a frequency of 2,1 MHz supplied the generating double meander, the signal of detecting meander coil was processed by means of receiver with a gain of 30 dB. The measurement has proved the proper function of the new shape of the transducer and its ability to generate symmetric mode of the Lamb wave, useful for the non-destructive testing of conducting films.

5. CONCLUSION

At present the non-destructive testing represents very significant item of research in connection with increasing demands on safety and reliability of sophisticated, expensive and strategically important facilities, e.g. nuclear power plants. There are two groups of methods widely used. One of them is based on the investigation of eddy currents induced in a surface layer of the tested body; the second one is based on investigation of propagation of acoustic waves in the body. Contact-less EMAT is a very convenient in this field and because of its low effectiveness the special shape of generating and detecting coil is intensively improved. Significant progress has been achieved in the last 10 years. Our qualitatively new design of the generating coil solves some problems mentioned in the quoted literature.

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