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THE APPLICATION OF THE ELECTROMAGNETO-ACOUSTIC METHOD TO NON-DESTRUCTIVE TESTING

Summary. The paper presents a brief overview of the main features of the electromagneto-acoustic method, which is used for noncontact generation and reception of ultrasonic waves. This overview includes, in particular, basic configurations of transducers, used for the generation and reception of various types of ultrasonic waves, discussion of electronic circuits associated with the transducers and the most important applications of the method to nondestructive testing of materials.

ZASTOSOWANIE METODY ELEKTROMAGNETYCZNO-AKUSTYCZNEJ W BADANIACH NIENISZCZĄCYCH

Streszczenie. Praca zawiera bardzo skrótowy przegląd głównych zagadnień dotyczących metody elektromagnetyczno-akustycznej, która jest stosowana do bezstykowego wytwarzania i odbioru fal ultradźwiękowych. W szczególności w pracy przedstawiono podstawowe konfiguracje przetworników, służące do wytwarzania i odbioru różnego rodzaju fal ultradźwiękowych, układy elektroniczne współpracujące z tymi przetwornikami, a także najważniejsze zastosowania tej metody w badaniach nieniszczących materiałów.

Introduction

Ultrasonic methods are among the most important and commonly used methods of nondestructive testing and evaluation of materials. The development of transducers, electronic circuits and methods of signal processing has led to the wide availability of ultrasonic instruments that make the detection, localisation and sizing of flaws, as well as the measurements of such quantities as thickness, velocity of ultrasonic waves etc., easy, fast, reliable and safe. Ultrasonic waves of a few MHz frequency are generally exited and detected with piezoelectric transducers. Such transducers have to be coupled with the surface of the object under test by means of some coupling medium, usually water of oil. In some cases the need for this medium makes the test difficult or even impossible to perform. For this reason, research into noncontact methods of generation and reception of ultrasonic waves has been carried out over the last three decades. Among various ultrasonic probes developed for noncontact operation, the ElectroMagneto-Acoustic Transducers (EMATs) have proved to be the most useful and attractive, at least with respect to their simplicity and cost.

The paper outlines the work on EMATs that has been carried out in the Institute of Electronics at the Silesian Technical University of Gliwice (for a through overview of problems associated with EMATs see reference).

Principle of electromagneto-acoustic transduction

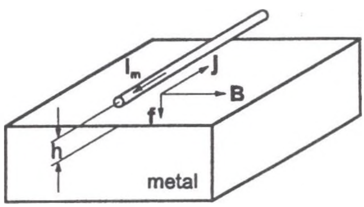

Fig. 1. Principle of electromagneto-acoustic generation of ultrasonic waves
Rys. 1. Zasada wytwarzania fal ultradźwiękowych metodą elektromagnetyczno-akustyczną

The principle of electromagneto-acoustic generation of ultrasonic waves is illustrated in Fig. 1. An EMAT consists, basically, of a winding and a magnet. The winding, which is located very close to the surface of a metal object under test, is fed with high frequency (usually a few MHz) current that induces eddy currents in the surface layer of the object. Their distribution is dependent on the shape of the winding. The eddy currents interact with a strong, steady magnetic field, generated by the magnet, and the resulting Lorentz force produces stress that is exerted on the surface layer of the metal. This stress is a source of ultrasonic waves that propagate into the bulk of the object or along its surface. The reception of ultrasonic waves with this method is based on reverse phenomena. The vibration of the surface of the conducting medium in the magnetic field produces eddy currents. The electromagnetic field generated by these currents is detected by the winding of the transducer.

The above described mechanism of transduction is characteristic for nonferromagnetic metals of high electric conductivity. In ferromagnetic metals the process of transduction is much more complex as it also involves magnetic forces and magnetostriction.

The mathematical description of the EMA transduction requires, first, solving of the Maxwell equations for a given setup of the transducer, to obtain the distribution of the electromagnetic field components. Then, the spatial stress distribution has to be determined, which is further substituted as an excitation to the acoustic wave equation. Even for the simplest case, i.e. the eddy current mechanism of transduction, the precise final solutions can be presented in the integral form only. To obtain the results that can be useful from the technical point of view, these integrals are usually calculated by substitution of some approximating functions or with the application of numerical methods.

As it was mentioned previously, the mathematical model of transduction in ferromagnetic metals is much more complex. Three mechanisms of transduction have to be taken into account and due to the nonlinearity of the material the contribution of individual mechanisms into the total process of transduction is highly dependent on the actual magnetic bias.

For these reasons, various approaches to the approximate mathematical modelling of EMATs can be found in available papers dealing with this problem. A detailed overview and discussion of these approaches is given in the reference.

Configurations of EMATs

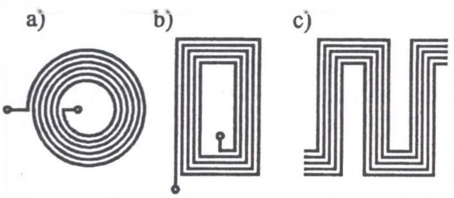

Fig. 2. Typical windings used in EMATs: a) spiral coil, b) frame, c) meander coil
Rys. 2. Typowe uzwojenia przetworników EMA: a) spiralna cewka, b) ramka, c) meander

With EMATs various types and polarisations of ultrasonic waves can easily be generated and detected. The type of ultrasonic wave is basically dependent on the shape of the transmitter/receiver winding and its location with respect of the poles of the magnet. The typical shapes of windings used in EMATs are shown in Fig. 2.

The most common types of ultrasonic waves that can be obtained with EMATs operating in the configurations shown in Fig. 3 are as follows:

- longitudinal waves that propagate normally or at some angles to the surface of the object,
- shear vertical (SV) waves (the plane of polarisation is perpendicular to the surface of the material) that propagate normally or at some angles to the surface of the object under test,
- shear horizontal (SH) waves (the plane of polarisation is parallel to the surface of the material) that can propagate at an almost arbitrary angle to the surface of the object,
- surface (Rayleigh) waves,
- Plate (Lamb) waves.

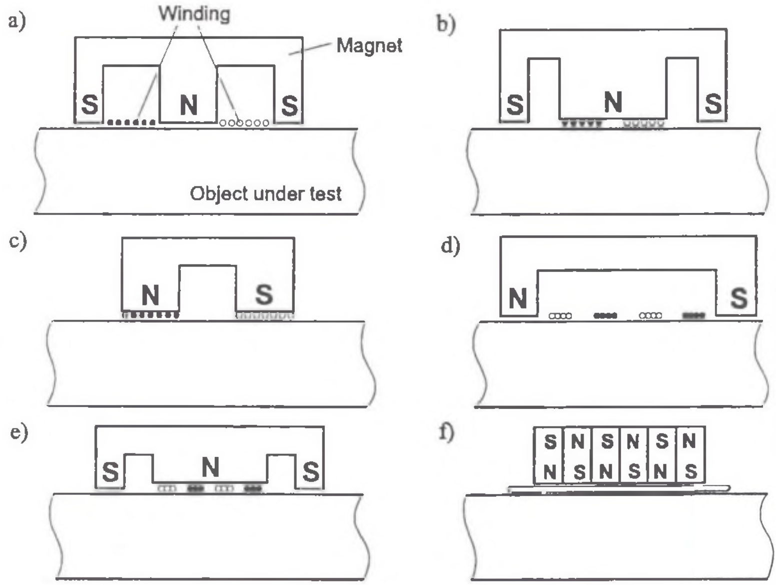

Fig. 3. Basic configurations of EMATs: a) normal transducer with a spiral or frame coil for longitudinal waves, b) normal transducer with a spiral coil for shear waves, c) normal transducer with a frame for shear waves, d), e) oblique entry transducer with a meander coil for longitudinal or SV waves, transducer for surface or plate waves, f) transducer with a frame for SH waves

Rys. 3. Podstawowe konfiguracje przetworników EMA: a) przetwornik normalny z cewką spiralną lub ramką na fale podłużne, b) przetwornik normalny ze spiralną cewką na fale poprzeczne, c) przetwornik normalny z ramką na fale poprzeczne, d),e) przetwornik kątowy z cewką meander na fale podłużne lub poprzeczne SV, na fale powierzchniowe lub płytowe, f) przetwornik z ramką na fale poprzeczne SH

Basic features of EMATs

One of the most important parameters used to characterise ultrasonic transducers is the efficiency of conversion of electric energy into mechanical energy and vice versa. For EMATs this efficiency is usually expressed as the transfer impedance, which is defined as the ratio of the maximum voltage across the receiver coil and the maximum current flowing through the transmitter coil. It can be shown that for nonferromagnetic metals the efficiency of EMA transduction is proportional to the square of flux density of the steady magnetic field. Nevertheless, the voltage received by an EMAT can be of the same order of magnitude as the signal obtained with piezoelectric transducers only when the magnetic field of, more or less, 10 T is applied. For this reason EMATs should produce the magnetic field in the area of transduction as strong as possible and their transmitter coils should be excited with pulses reaching 1-2 kV or more.

The above mentioned relationship is not always true for ferromagnetic metals. It has been found experimentally that for such metals there is sometimes optimum magnetic field strength at which the overall efficiency of EMA transduction becomes maximum.

The generally low efficiency of EMATs becomes surprisingly high (the received voltage reaches tens of mV) for ferromagnetic metals as temperatures approaching the Curie point. This phenomenon is attributed to the increased magnetostriction near this temperature. For this reason a number of reported industrial applications of EMATs dealt with testing of steel products at a high temperature.

The efficiency of EMA transduction is strongly affected by, so called, lift-off effect. This means a decrease in the amplitude of the received signal when the transducer is moved away from the object under test. The lift-off effect results from the fact that an increase in the air gap between the face of the transducer and the surface of the metal reduces the electromagnetic coupling between the transmitter/receiver winding and the metal as well as the magnetic field strength in the area of transduction. For real EMATs the signal drop caused by the lift-off effect usually is, roughly, in the range from -10 dB/mm to –20 dB/mm.

Because of the difficult methematical modelling of EMATs many of their characteristics have been found experimentally. A large selection of the papers on the subject (over 200) is referenced in the monograph of the author, specified at the end of this paper. Due to the concise form of this paper they are nor mentionad here.

Electronic circuits required for EMATs

The drivers used to excite EMATs usually consist of a capacitor that is charged to a few kilovolts and then discharged through the transmitter coil. The peak value of the current flowing through the coil reaches tens of amperes or more. The frequency of damped oscillation and the generated ultrasonic wave is determined by the respective parameters of the capacitor and the coil. This means that the electronic switch that connects the capacitor and the coil should withstand high voltage and high current and feature short switching times. Initially thyratrons or other electronic tubes were used for this purpose. Then thyristors gained popularity and such switches were also used in a driver designed by the author. Another problem associated with the design of drivers for EMATs is an appropriate method of high voltage generation. The most efficient solution is to use a switching converter but the interference produced by such a voltage source makes the reception of ultrasonic echoes very difficult. To eliminate the interference, a modified flyback converter was designed (see reference). The idea of this solution, shown in Fig. 4, consists in producing the required voltage in one cycle, before the thyristor switch is triggered. The operation of the converter is blocked for the time necessary to receive the echoes, so no interference is generated over this period. The same idea has been also applied in a recent disign of a 1 kV driver in which an IGBT switch is used instead of thyristors connected in series.

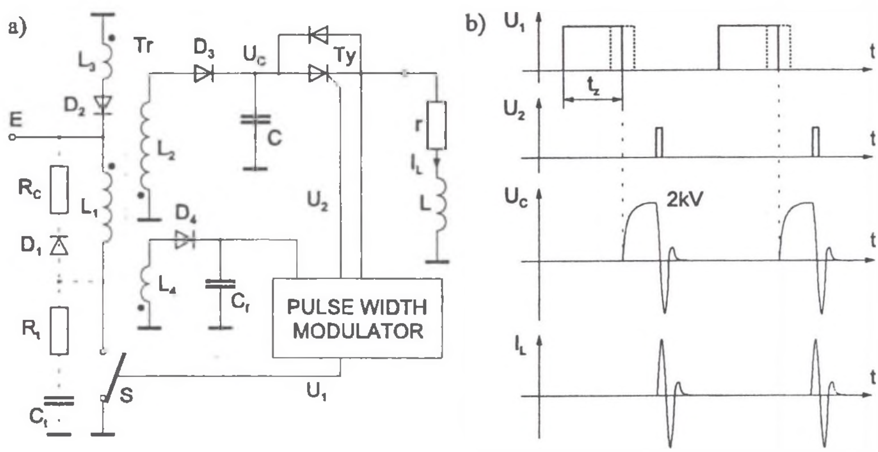

Fig. 4. Simplified circuit diagram of a switch-mode driver (a) and its timing diagrams (b)
Rys.4. Uproszczony schemat nadajnika z przetwornicą impulsową (a) i występujące w nim przebiegi czasowe (b)

The voltage received by EMATs is often as low as tens of microvolts. This means that in order to display the echoes with conventional ultrasonic flaw detectors an additional preamplifier has to be used, with a gain of, roughly, 50 dB. The input of this preamplifier should be protected by a limiter against the transmitter pulse that appears also across the receiver coil. The transients coused by the transmitter pulse make the preamplifier unable to receive any echoes for a few microseconds and this corresponds to a dead zone of at least 10-20 mm. Unfortunately, in contrast to piezoelectric transducers, where suitable delay lines can be used, no methods have been developed to reduce the considerably high dead zone of EMATs.

Apart from drivers and receiver amplifiers, electronic circuits can also be used to minimise the influence of lift-off on performance of EMATs. A simple method has been suggested by the author. This method can be applied to the transmitter and receiver transducers separately and is based on the properties of resonant circuits. The impedance of a coil is dependent on its distance from a metal surface and so are the resonant frequency and the quality factor of a circuit formed by the transmitter/receiver coil and a capacitor connected to it. The capacitor should be selected so that the resonant frequency of the transducer that touches the sample is higher than the frequency of the ultrasonic wave. When the transducer is moved away from the sample, the reduction of the signal amplitude, resulting from weaker electromagnetic coupling and magnetic field strength, is to some extent compensated thanks to a decrease in the resonant frequency and an increase in the quality factor of the respective resonant circuit. A more sophisticated method of lift-off compensation requires the use of a voltage controlled amplifier. The control signal should be dependent on the distance between the transducer and the object under test. A convenient method of obtaining such a signal is to produce a voltage signal that is proportional to the peak current in the transmitter coil. The latter is a function of the impedance of the transmitter coil and this impedance varies with the considered distance.

Application of EMATs

The main areas of applicatio, where WMATs may have some advantages over conventional ultrasonic probes and some prototype devices were reported by researchers, are as follows:

- Thickness measurement

  Depending onthe method of measurement (e.g. pulse echo technique, resonance method) thickness from below 1 mm up to hundreds of mm can be measured with the accuracy of, typically, 1%. Normal entry shear wave transducers are usually used for this purpose. This measurement is also used for testing the condition (e.g. corrosion) of pipelines, tanks etc.
- Testing at a high temperature

  This application usually takes advantage of the previously mentioned sharp increase in the efficiency of longitudinal wave transducers around the Curie point, although tests of nonferromagnetic metals (e.g. aluminium) at high temperatures have been also reported.

- Railway transport

  Normal and angle shear wave transducers can be used for testing rails and surface wave transducers may be used for testing wheel rims for cracks.

- Testing of welds

  Angle shear wave transducers are used for detecting flaws in welded joints. The research into this application includes work on focusing transducers.

- Measurement of ultrasonic wave velocity

  Attempts have been made to apply the measurement of wave velocity to the determination of structure of materials, stress measurement etc. The birifrengence method is often used.

- Testing of ultrasonic probes

  Receiver EMATs are used for laboratory measurements of acoustic field distribution and directivity patterns.

The work of the author has been mainly concentrated on the application of EMATs to flaw detection and thickness measurement. A number of longitudinal and shear wave transducers have been designed, configured according to Fig. 3a,b,c.

The transducer for longitudinal waves of Fig. 3a enables testing of nonferromagnetic metals. Its sensitivity is sufficient to receive an echo from a 2 mm diameter flat bottom hole made in the bottom of a 50 mm high aluminium cylinder. Another transducer, with a frame winding (Fig. 3c), can detect a 2 mm diameter through hole, drilled in the neck of a railway rail.

As for thickness measurement, a thickness gauge has been designed that enables measurement in the range from 5 mm to 100 mm with the accuracy of ±0,1 mm. It uses the transducer of Fig. 3b, with a spiral coil, which operates at a fequency of about 1 MHz. To produce a strong magnetic field in the sample, a pulse electromagnet is used. Recently some experiments have been carried out in order to examine the feasibility of decreasing the lower limit of the measurement range. With a miniature transducer (configured as in Fig. 3c), including a rare earth magnet and operated at about 2,5 MHz, well separated echoes have been obtained from a 2,5 mm thick steel sheet.

To enable the measurement of directivity patterns of ultrasonic probes, receiver transducers and a suitable measurement stand have been also designed. Thanks to the partial screening of the receiver winding the active area of reception is limited to about 2 mm^2.

Conclusions

EMATs can be an interesting alternative to piezoelectric transducers in these applications where the provision of liquid coupling is difficult or impossible (tests performed at a high temperature, field tests or tests performed at a high speed on production lines). However, because of their low efficiency most descriptions concern prototype devices, of which the usefulness for nondestructive testing has been often examined in laboratory conditions only. There are few examples of practical EMATs that have been available on the market. Such devices are by no means versatile as in order to overcome their deficiencies they have to be optimised for a specific application.

The drawbacks of EMATs are mainly associated with the transmitters, as they require high voltage excitation, which results in a relatively large dead zone of the whole system. There is possibility of eliminating these problems by using hybrid transducers, which consist of a laser transmitter and an EMA receiver. The laser generation of ultrasonic waves consists in creating stress on the surface of the object under test thanks to rapid heating of this surface by a laser beam. Such hybrid transducers have been examined since the mid eighties and may prove to be the optimum solution for noncontact ultrasonic testing of materials.

Bibliography

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Streszczenie

Praca zawiera skrótowe omówienie podstawowych zagadnień związanych z przetwornikami elektromagnetyczno-akustycznymi (EMA), które pozwalają na bezstykowe wytwarzanie i odbiór fal ultradźwiękowych w ośrodkach metalicznych. Omówienie to opiera się zarówno na studiach literaturowych, jak i pracach własnych autora.

Istota wytwarzania fal ultradźwiękowych metodą EMA polega na oddziaływaniu prądów wirowych (w metalach nieferromagnetycznych) lub – w przypadku bardziej ogólnym – zmiennego pola magnetycznego, wytwarzanych przez uzwojenie nadawcze przetwornika, ze stałym polem magnetycznym, wytwarzanym przez przetwornik w badanym obiekcie. Odbiór fal ultradźwiękowych odbywa się na zasadzie wykorzystania zjawisk odwrotnych.

O rodzaju wytwarzanej lub odbieranej fali ultradźwiękowej decyduje przede wszystkim konfiguracja przetwornika, tzn. kształt jego uzwojenia nadawczego/odbiorczego oraz jego lokalizacja w stosunku do nabiegunników przetwornika. Metodą EMA można generować lub odbierać fale podłużne, poprzeczne o różnej polaryzacji, powierzchniowe i płytowe.

Głównymi wadami przetworników EMA jest ich mała skuteczność przetwarzania i tzw. zjawisko unoszenia. Skuteczność przetwarzania jest najczęściej określana jako stosunek amplitudy odebranego sygnału do amplitudy wymuszenia. Echa odbierane przez przetworniki EMA są zazwyczaj o co najmniej 40-60 dB niższe niż w przypadku przetworników piezoelektrycznych. Ze względu na tę małą skuteczność przetworniki EMA muszą być pobudzane impulsami o amplitudzie sięgającej kilku kilowoltów. W nadajnikach muszą być zatem stosowane szybkie klucze elekroniczne o wysokiej wytrzymałości napięciowej i prądowej. Mogą to być tyratrony, tyrystory, a w ostatnich latach stosowane są także tranzystory mocy MOSFET i IGBT. Zjawisko unoszenia polega na zmniejszaniu się skuteczności przetwornika, gdy jest on oddalany od badanego materiału. Spadek amplitudy sygnału może sięgać 20 dB/mm. Możliwe są jednak pewne metody kompensacji tego zjawiska.

Główne zastosowania przetworników EMA, które najczęściej ograniczają się jednak do konstrukcji prototypowych, to pomiary grubości, badania gorących wyrobów, badania szyn kolejowych, rurociągów i zbiorników, a także połączeń spawanych, pomiary prędkości fal ultradźwiękowych, badania głowic ultradźwiękowych itp.