

MEASUREMENT OF SURFACE DISPLACEMENT EXCITED BY EMAT TRANSDUCER

*Petr Fidler*¹, *Petr Beneš*²

¹ Brno University of Technology, Faculty of Electrical Engineering and Communication, Brno, Czech Republic, xfidle00@stud.feec.vutbr.cz

² Brno University of Technology, Faculty of Electrical Engineering and Communication, Brno, Czech Republic, benesp@feec.vutbr.cz

Abstract – The article discusses the measurement of surface displacement of an electrically conductive solid material. Deflection is excited by electro-magneto-acoustic transducer (hereinafter referred to as EMAT). Measurement is realized by laser interferometer. In our research the precise surface displacement measurement is necessary for two reasons. First is EMAT transducer numerical model convergence verification, second is the experimental optimization of EMAT transducer parameters such as sensitivity, frequency and direction characteristics. Used laser interferometer allows the accurate assessment of surface displacement in a relatively small item, which gives an advantage over using piezoelectric acoustic emission sensors that are limited by aperture effect at small wavelengths. In addition, laser interferometer is capable of surface displacement measuring directly under the EMAT device, which is very difficult with using other methods.

Keywords: EMAT transducer, laser interferometer, surface displacement

1. INTRODUCTION

EMAT is a device designed to generating and sensing of acoustic emission signal. Its principle (as shown in Figure 1) is based on the mutual interaction of static magnetic, dynamic electric and magnetic and dynamic mechanical fields [1].

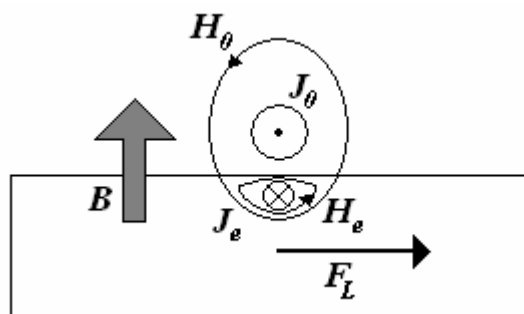


Fig. 1. Basic principle of EMAT [1], [6]

Transmitting and receiving part of the EMAT consists of a static magnetic field source (permanent magnet,

electromagnet) and source of dynamic electromagnetic field (linear coil). Mechanical force field arises as a result of interaction of the first two fields in the solid material, which is located under the EMAT. The function principle of the transmitting part, which is devoted to this text, is different when the ferromagnetic or non-magnetic electrically conductive material is used. In the first case the action of force is realized by alternating component of magnetostrictive force [1]. In the second case, which is used in a practical experiment, the action of force is consequence of the eddy currents induced in the material as result of coil dynamic magnetic field and static magnetic field of permanent magnet interaction. The resulting volume force [2] (Lorentz force) causes the creation of time-variable mechanical stress in the immediate distance of the material surface and the associated distortion of the surface. Part of the power of action energy propagates further in material by means of elastic waves. Direction and type of elastic waves is dependent on the arrangement of described physical fields. For practical experiment is chosen Rayleigh wave EMAT type shown in Figure 2 [1].

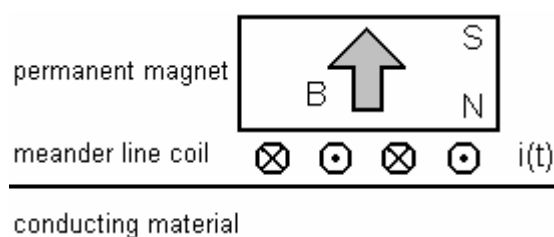


Fig. 2. Rayleigh wave EMAT type [1]

The main advantages of EMAT are the ability of noncontacting generation and sensing of acoustic emission signal and better shape of frequency response compared with piezoelectric generators. The main disadvantage is very low sensitivity. Increase of sensitivity with regard to the appropriate frequency response and direction characteristics is the primary concern of our research. This can be achieved by combining the two processes. The first is the numerical model, which includes the calculation of elasticity functions [2]. Vertical displacement of the solid material surface is only one of these functions, which can be experimentally

verified. To verify the convergence of calculated action of force is necessary to measure the displacement directly under the EMAT and further in defined distance from the EMAT to verify the convergence of the elastic wave propagation calculation. With using of precise surface displacement measurement it is possible to realize the experimental optimization of above-mentioned EMAT parameters. Due to the lack of EMAT parameters presentation it was necessary to measure the normal displacement generated by EMAT with using piezoelectric acoustic emission sensor UT1000 (Physical Acoustic Corporation). Given the value of the UT1000 sensitivity at chosen frequency [3] was calculated the presumptive displacement value at a distance of approximately 100 mm from the EMAT in range of tens of picometers. This value is just above the resolution level of the used laser interferometer Polytec OFV-505.

2. PRACTICAL EXPERIMENT

There was designed an EMAT modification (Figure 3) for the practical experiment, which allows the surface displacement measurement directly under the EMAT. To evaluate the displacement at a greater distance is used typical EMAT design (Figure 2). For measuring and displacement to voltage signal transforming the laser interferometer Polytec OFV-505 with the evaluation unit OFV-5000 is used. Measurements carried out on a dural sample.

2.1. Design of EMAT transmitting part

A pair of permanent neodymium magnets is the static magnetic field source for displacement measurement directly under the EMAT. A couple of permanent magnets in the selected arrangement has proved as the best choice, compared to identically magnetized annular magnet showed a significantly higher magnetic induction component normal to the tested sample surface and thus a higher efficiency of transmitting EMAT.

For surface displacement measurement in defined distance from EMAT is used single permanent magnet. Linear coil for both measurements is of meander type, whereas the winding span is chosen on the basis of half of acoustic wavelength λ_R [1] derived from the frequency f of power signal according to (1).

$$\lambda_R = \frac{0,87 + 1,12\mu}{f(1 + \mu)} \sqrt{\frac{E}{2\rho(1 + \mu)}} \quad (1)$$

where μ is Poisson ratio, E is modulus of elasticity and ρ is testing sample density. Material properties of used tested material are described in table 1. Initially chosen for the frequency of 500 kHz is appropriate 5,89 mm wavelength in dural sample [4]. On the basis of observation [5] is used the proportionality of induced electromotive voltage on time-variable coupled magnetic flux [6] and linear coil is made by several threads of copper wire with a diameter of 0.1 mm. The resulting structure is simplified shown in Figure 3. Photos of designed modified EMAT type

are shown in figure 4 and photos of basic EMAT type are shown in figure 5.

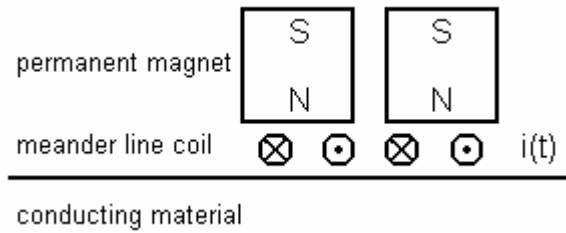


Fig. 3. Modification of Rayleigh wave type of EMAT

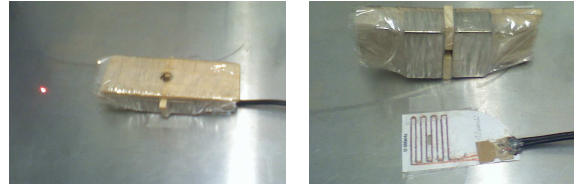


Fig. 4. Photos of designed modified EMAT type

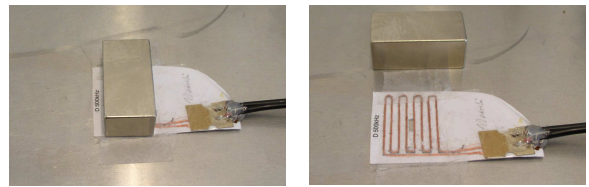


Fig. 5. Photos of designed basic EMAT type

Principal scheme of basic EMAT type is shown in Figure 2. Modified type of EMAT is used in version 1 of practical experiment, basic type of EMAT is used in version 2 of practical experiment. Description of the parameters of both implementations is given in Table 1.

Table 1. Used EMAT parameters and tested material properties.

EMAT type	Description
1 (modif.)	<p>application: displacement measurement under coil</p> <p>magnet: 2xNdFeB magnet (38x15x20mm), $B_r = 1,38$ T, $H_c = 876$ kA/m</p> <p>coil: material: copper, span: 2,945mm, number of bundle: 10, number of conductor in bundle: 10, diameter of conductor: 0,1mm, length of meander: 28mm</p>
2 (basic)	<p>application: displacement measurement in 100mm distance from coil</p> <p>magnet: 1xNdFeB magnet (38x15x20mm), $B_r = 1,38$ T, $H_c = 876$ kA/m</p> <p>coil: material: copper, span: 2,945mm, number of bundle: 10, number of conductor in bundle: 10, diameter of conductor: 0,1mm, length of meander: 28mm</p>
Tested specimen properties	<p>material: dural</p> <p>dimensions: 260mm, 430mm 6mm</p> <p>Poisson ratio: 0,34</p> <p>modulus of elasticity: $72 \cdot 10^3$ MPa</p> <p>density: $2700 \text{ kg} \cdot \text{m}^{-3}$</p>

2.2. Laser interferometer description

Laser vibrometer OFV-5000 measures displacement and velocity. It has customised several decoders for this problem. In our experiment is elected auxiliary decoder DD-300, which measures displacement in 50 kHz to 2MHz frequency band. Range restriction of $\pm 75\text{nm}$ is negligible considering the presumptive surface displacement in the tens of picometers. The level of noise in the range is less than $0.05 \text{ pm}/\sqrt{\text{Hz}}$, implying noise effective value of about 25pm in the 50 kHz to 2MHz frequency band. The measured value of the input noise is shown in Figure 6.

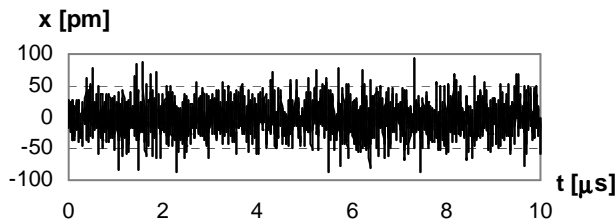


Fig. 6. Input noise of laser interferometer

Laser interferometer resolution is for used band $25\text{nm}/\text{V}$ with a maximum additional error $+0.5/-1\text{dB}$. Measured RMS of noise is approximately 25 picometers.

2.3 Electric properties of designed EMAT

Meander line coil impedance is important parameter limiting EMAT acoustic wave generator. Simplified equivalent circuit diagram is shown in figure 7.

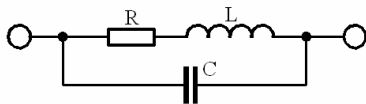


Fig. 7. EMAT equivalent circuit diagram

Dominant part of equivalent circuit diagram impedance is inductivity. Inductivity is proportional to length of meander and number of windings. Decreasing of inductivity is caused by eddy currents induced in tested material and in permanent magnet. EMAT impedance modulus dependence on frequency is shown in figure 8.

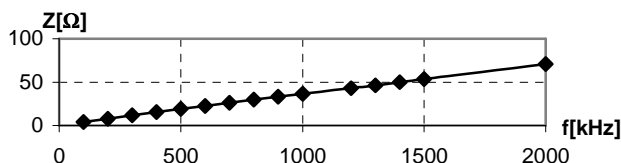


Fig. 8. EMAT equivalent circuit diagram

500 kHz frequency impedance value is approximately 40Ω . According to generator output impedance the supposed supply current on 500 kHz frequency should have been moving around 110mA. Measured EMAT parameters are $R=17,8\Omega$, $C=7,6\text{nF}$ and $L=10,3\mu\text{H}$.

2.3. Experiment description

As it was mentioned above the experiment is divided into two parts. The first is displacement measuring directly

under the EMAT. Used type of EMAT is described in Figure 3 and 4. For the evaluation of measurement results the oscilloscope Agilent 54622D is used, the function generator Agilent 33220A driven by program in LabVIEW environment is used like source of exciting signal. According to supposed generation of standing waves is used temporary exciting signal. Standard exciting signal for acoustic emission sensors calibration is harmonic pulse with sine square envelope. Open circuit signal generator amplitude is 10V with output impedance of 50Ω , length of harmonic pulse is $100\mu\text{s}$ with frequency 500 kHz. For measuring of exciting signal the AC current probe Tektronix P6022 with sensitivity $1\text{mV}/\text{mA}$ is used. As mentioned in Section 2.1, meander linear coil is wound of the ten conductors and hence the mean meander span value is not exactly 2,945mm.

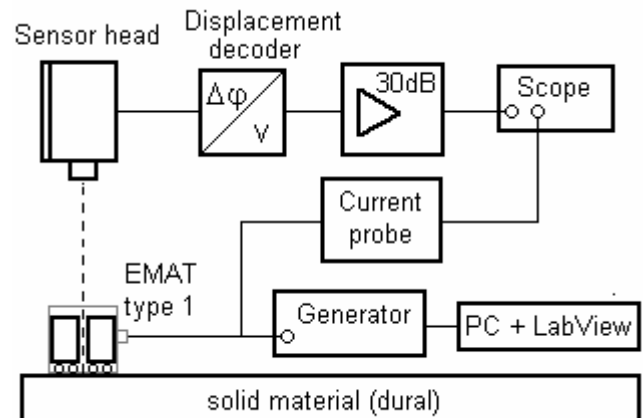


Fig. 9. Version 1 of practical experiment

In the experiment version 2 is used EMAT in the implementation from Figure 2 and 5. Measured displacement is the result of Rayleigh elastic wave propagating close to material surface. Version 2 of experiment is graphically illustrated in Figure 10.

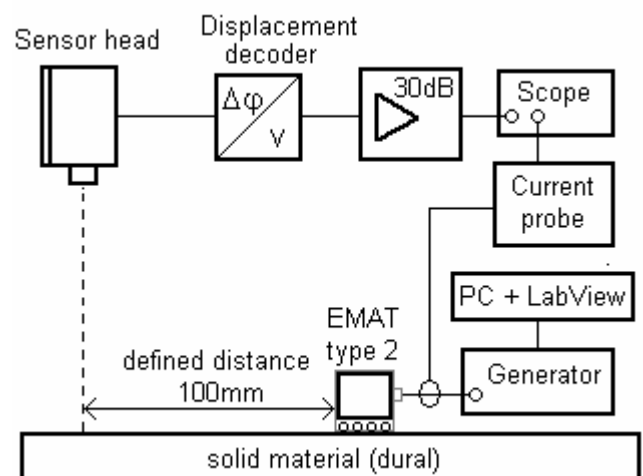


Fig. 10. Version 2 of practical experiment

In both experiment versions is the head of the sensor attached to the robust construction. Dural plate is located at

the construction, so there is no mutual moving between tested surface and sensor head. Low-frequency noise is eliminated the lower limit decoder frequency of 50 kHz.

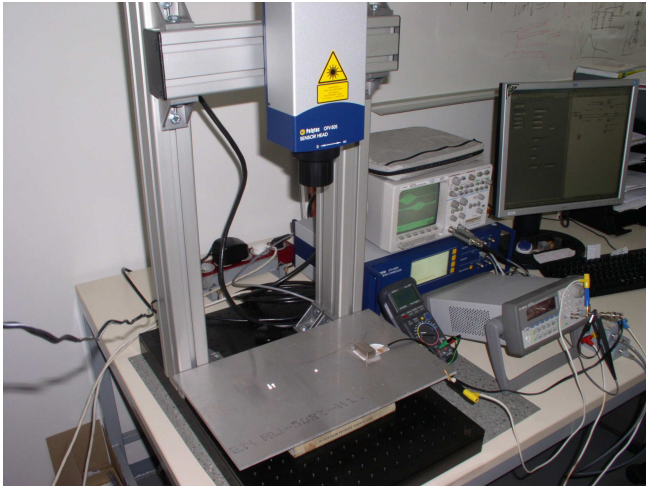


Fig. 11. Photo of measuring workplace

2.4. Measurement results

Due to high level of noise in the frequency range 50 kHz to 2MHz it is necessary to use averaging in time domain for greater relevance of the results. Number of averaged waveforms is 512 in both experiments. In both versions of experiment the response on excitation with single harmonic pulse at a frequency of 500 kHz is monitored. Considering the limited size of dural sample the longer excitation leads to signal distortion caused by the elastic wave sample edges reflection and the possibility of standing waves generation.

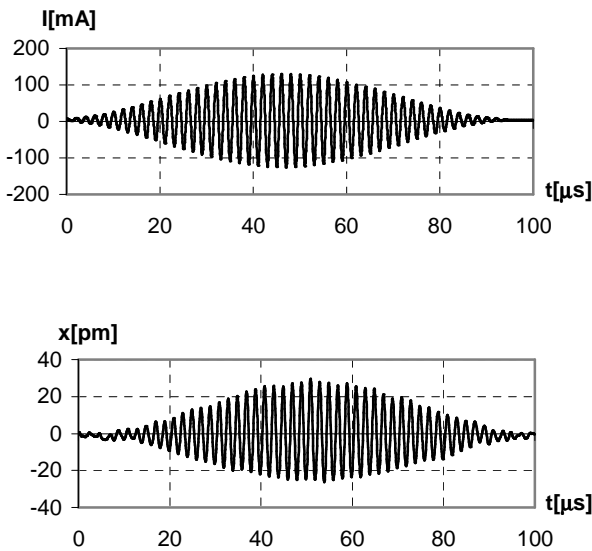


Fig. 12. Excitation current waveform and measured averaged surface displacement (experiment version 1)

In first waveform of figure 12 is exciting current measured with AC current probe shown. Maximal exciting current value is 126mA, which corresponds with theoretical presumptions. Surface displacement response measured with

laser interferometer reaches maximal value of 29pm. There is probable inertial force influence noticeable in response waveform, which causes slower decreasing of displacement value during decreasing of exciting signal. In figure 12 is longer time window, where edge reflections are noticeable. Times of arriving of signal maximum (154μs, 164μs, 214μs and 221μs) are signed by arrows. It means, that there happens overlapping useful signal and signal reflection in time area of approximately 100÷120μs.

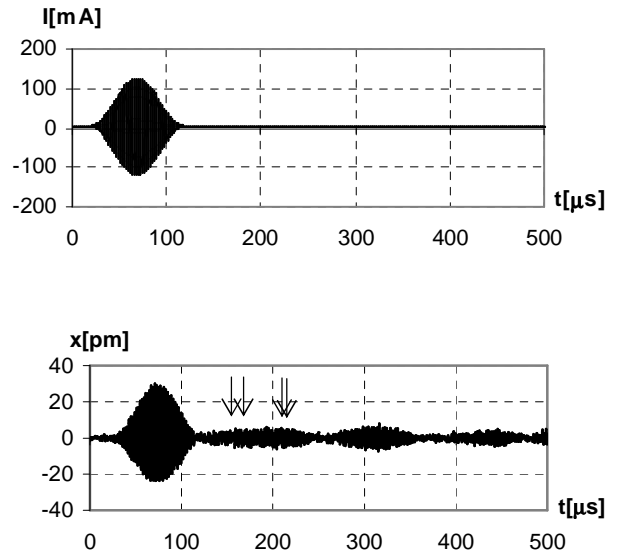


Fig. 12. Excitation current waveform and measured averaged surface displacement with sample edges reflections (experiment version 1)

Measured results from version 2 of practical experiment are show in figure 13.

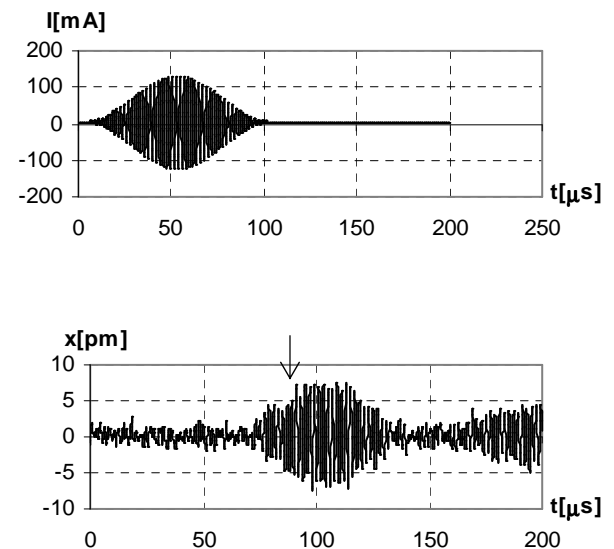


Fig. 13. Excitation voltage waveform and measured averaged surface displacement (experiment version 2)

Maximal amplitude of response signal reaches approximately 8pm value. Decreasing of amplitude is caused by ultrasonic wave damping [4]. According to damping dependence on wave frequency and distance from ultrasound source, the value of ultrasonic wave damping is determined as $0,12\text{dB}\cdot\text{mm}^{-1}\cdot\text{MHz}^{-1}$.

Compared to theoretical presumption the arriving time of signal response maximum is delayed approximately by $15\mu\text{s}$. This event, which occurs in frequency band approximately 100kHz around frequency 500kHz (generally around frequency of maximal efficiency of designed EMAT generator), can be caused by waveform normal line direction change and subsequent wave spreading through reflections from bottom and top sample sites or it can be caused by another at present unknown effect.

In figure 12 are shown ultrasonic waveform with multiple reflections on sample edges.

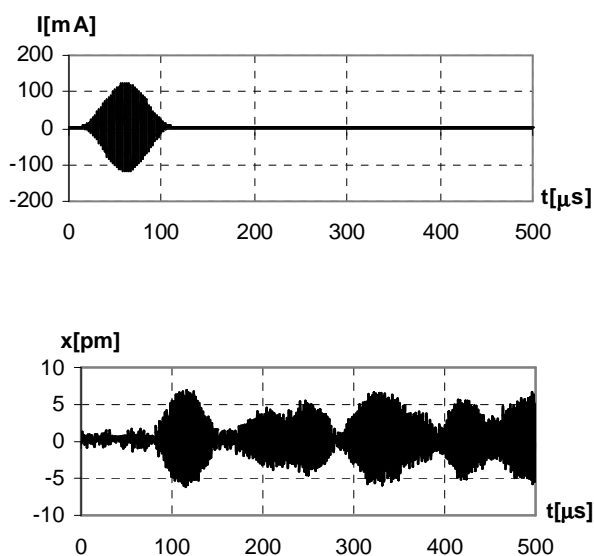


Fig. 12. Excitation current waveform and measured averaged surface displacement with sample edges reflections (experiment version 2)

4. CONCLUSIONS

The article discusses the measurement of solid material surface displacement generated by EMAT device. The aim is to determine the displacement value at single point generated by EMAT for subsequent comparison with the numerical model, as well as to optimize the EMAT parameters. Using a laser interferometer the surface displacement directly under and at defined distance from

EMAT was measured. The amplitude value of surface displacement is moving around approximately 8 picometers and 26 picometers values. The aim of further research will be increase these values. Averaging at time domain was necessary because of relatively high value of the laser interferometer input noise and without the implementation of the results is not nearly as robust. The results form a good basis for verification of the numerical model convergence and the subsequent optimizing the parameters of EMAT equipment for the acoustic emission testing and secondary acoustic emission sensors calibration. In future will be necessary replace used testing sample by cylindrical sample with dimensions enabling measuring of waveforms distortionless by edge reflections.

ACKNOWLEDGMENTS

This work has been supported by Grant Agency of Czech republic, grant no. GA 102/09/H082 Sensors and intelligent sensor systems.

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