

A Low Noise Preamplifier Circuit for a Highly Sensitive EMAT Transducer for Picometer-scale Ultrasonic Displacement Measurements

S.Boonsang and R.J. Dewhurst

Abstract— We present a novel design of electromagnetic acoustic transducer (EMAT) for non-contact ultrasonic measurements. A recent prototype of the EMAT sensor has miniaturized the receiver size (1.0 cm diameter). It was incorporated with a specially designed low noise preamplifier. Calibration procedures with a Michelson interferometer revealed that the EMAT sensor detected small displacement amplitudes as low as 1.0 ± 0.2 pm in aluminium with a signal bandwidth up to 7.5 MHz (-3dB). Alternatively, this sensitivity figure can be expressed in term of noise-equivalent displacement spectrum as 4.2×10^{-17} m.Hz^{-1/2}. The absolute sensitivity of the EMAT was 1.98 ± 0.5 V.pm⁻¹ for the detection of longitudinal waves. The paper also presents the comparative study of the performance of the EMAT sensor with various ultrasonic transducers.

Index Terms—EMATs, Michelson Interferometer, Ultrasonic sensors.

I. INTRODUCTION

For non-contact ultrasonic measurements, EMATs have been investigated by many authors for more than two decades [1-5]. EMATs can generate and detect ultrasonic waves by means of electromagnetic transduction, which require no coupling substances. The basic design of EMATs consists of permanent magnets for setting up static magnetic fields within a material under investigation and a coil. In generation mode, the interaction of particle velocities v as results from ultrasonic waves and the magnetic flux density \vec{B} from EMAT permanent magnets produces eddy currents \vec{J} within the sample (about the skin depth of the sample) according to Lorentz force mechanism as following [6]:

$$\vec{J} = \sigma_c (\vec{v} \times \vec{B}) \quad (1)$$

where σ_c is conductivity of a conducting sample. These eddy

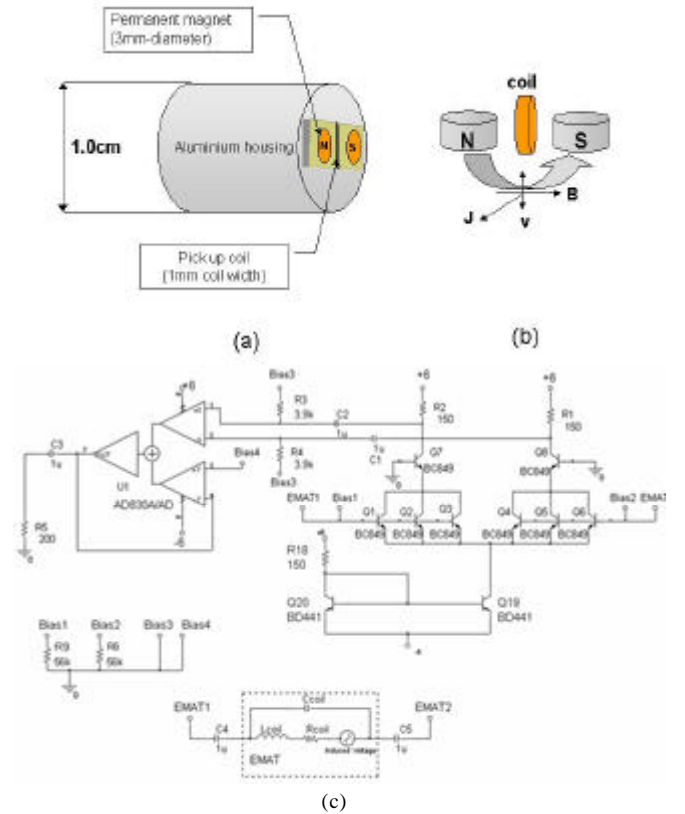


Figure 1(a) The general design of a highly sensitive miniaturized EMAT comprises of two permanent magnets attached to cylindrical aluminium housing with the radius of 1.0cm. A picked up coil was inserted between two magnets. (b) The diagram shows the model of an eddy current (J) created by the interaction between a static magnetic field (B) supplied by two permanent magnets and an out-of-plane ultrasound velocity (v). (c) The general design of a differential preamplifier for the EMAT. currents subsequently radiate secondary time-varying magnetic fields out of the sample body. Such magnetic fields are then picked up by an EMAT coil, which is normally placed at less than a millimeter above the sample surface. Induced voltages within the EMAT coil are the result from the time varying magnetic fields that cross the receiving area of the EMAT coil.

Several designs of EMATs for generation and detection of ultrasound have been proposed [1, 3, 4, 7-9]. The orientation of static magnetic fields supplied by permanent magnets and the

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geometry of a coil are the essential factors in determining ultrasound modes that EMATs are most sensitive. For in-plane EMATs, the direction of the magnetic field supplied by permanent magnet is normal to the sample surface, therefore, they are primarily sensitive to in-plane ultrasonic motions. A pancake-shape coil or a meander-line coil with a permanent magnet placed on the top of the coil are probably the most widely used in the generation mode [8, 10-13]. This is due to such coil shapes can be easily fabricated using print circuit boards (PCB) and it can be securely supplied by a large driving current (several hundred amperes, [12]) to efficiently induce eddy currents in a sample. In detection mode, a number of turns of a coil and its orientation (to receive as much time-varying magnetic flux as possible) are also important factors. The design of a coil of enamel coated, fine copper wire (0.06 mm diameter), wrapped around a 7.5 mm radius \times 5 mm thick, 1T DC NdFeB magnet may provide the better sensitivity than those from a pancake-shape coil or a meander-line coil design. This design was used as a hybrid laser/EMAT system for various potential NDE applications [5, 9, 14, 15].

In term of absolute ultrasonic displacement measurements, an EMAT sensor reported by [16] showed the minimum detectable displacement as low as 17 pm for a detection bandwidth of 1 MHz. Such a performance was comparable to air-couple capacitive transducer counterparts, which normally has larger stand-off distance [17, 18]. To improve the sensitivity of an EMAT sensor, a low noise preamplifier with an input impedance matching to an EMAT pickup coil can be employed. There is one report [19] that an EMAT sensor with a specially design shielding case together with a build-in preamplifier can be used to measure laser generated ultrasonic waves in welding environments with signal-to-noise ratio about 25 without signal averaging. However, information of minimum detectable displacement was not available in their report. In this paper, we demonstrate the EMAT performance improvement by introducing a novel design of an out-of-plane EMAT sensor and associated electronics. To quantify the sensitivity improvement, the absolute calibration procedure using a Michelson interferometer was employed. We also present the comparative study of the performance of the EMAT with various ultrasonic transducers.

II. THE DESIGN OF A SENSITIVE EMAT SENSOR

The design of the EMAT comprises of two Neodymium disc magnets (3mm diameter, 2mm height) embedded in a rectangular PCB board (6mm \times 8mm \times 1.5mm) attached to the face of a cylinder aluminium housing (5.0cm height, 1.0cm diameter). The outline of design is shown in Figure 1(a). The polarity of both disc magnets was arranged in opposite polarity (Figure 1(b)). The magnetic field penetrates a sample and sets up a static magnetic field in a sample. The magnetic field lines may be simply assumed to be a predominantly in-plane direction with in the samples. The out-of-plane velocity of incident acoustic waves (v) interacts with the static

magnetic field (B) set up by two disc magnets. This interaction creates eddy currents density (J), described by the Lorentz force, about the surface of the sample. A pick-up coil situated in between two disc magnets picks up the changes in a weak secondary magnetic field produced by such eddy currents

The EMAT coil is made up of enamel coated, fine copper wire wrapped around the PCB board in between two permanent magnets. The lateral width of the pick-up coil is about 1mm. The effective area of the EMAT coil is about 6mm² (3 \times 2mm) approximately. The signal received by the EMAT coil is fed to a special-designed low noise preamplifier.

The preamplifier arrangement that was adapted for the pick-up coil is shown in Figure 1(c). The coil was capacitively coupled to the differential input stage of a preamplifier. The resistances (R5-6) were to provide a bias current for the transistors of the differential stage and adjust the overall response of the preamplifier.

The paralleling of three ultra low noise transistors (BC849 with noise figure at 1kHz of 1.2dB, Fairchild Semiconductors) for each side of differential stages (Q1-6, shown in Figure 1 (c)) reduces the overall base spreading resistances by a factor of $\sqrt{3}$ [20]. Therefore, a decrease of the input equivalent noise voltage is similar. Another benefit from the paralleling three transistors is the reduction of an optimum (for the optimum noise performance sense) source resistance by a factor of 3, providing a better match for the low output impedance of a pick-up coil. The parallel stages increased the input noise current by a factor of $\sqrt{3}$ as well. In spite of this, it did not have a substantial effect to the overall noise performance of the preamplifier because of the low output impedance of the pick-up coil. Nonetheless, when paralleling three stages, the input capacitance of a preamplifier increases its value in proportional to 3. This increased capacitance value could potentially make the preamplifier resonate (at low frequency), when an EMAT's pick up coil (predominantly inductive characteristic) is used as an input.

The output from a cascode stage was capacitive coupled to a fully differential operational amplifier (AD830, Analog Devices). The active feedback topology of an Analog Devices AD830 operational amplifier are the important features to achieve a high common mode rejection ratio (CMMR of 100dB at 100kHz and 60dB at 4MHz) and a high common mode input impedance without sacrificing half the bandwidth as is formed with conventional discrete differential operational amplifiers.

III. ABSOLUTE CALIBRATION USING A MICHELSON INTERFEROMETER

It is well known that Michelson Interferometers can be used to measure an absolute out-of-plane ultrasonic displacement. In previous publications, they have been used to perform absolute calibrations of hydrophones [21, 22], and comparative studies of various wide-band ultrasonic transducers [16, 23-25].

A schematic diagram of a 5 mW Michelson interferometer

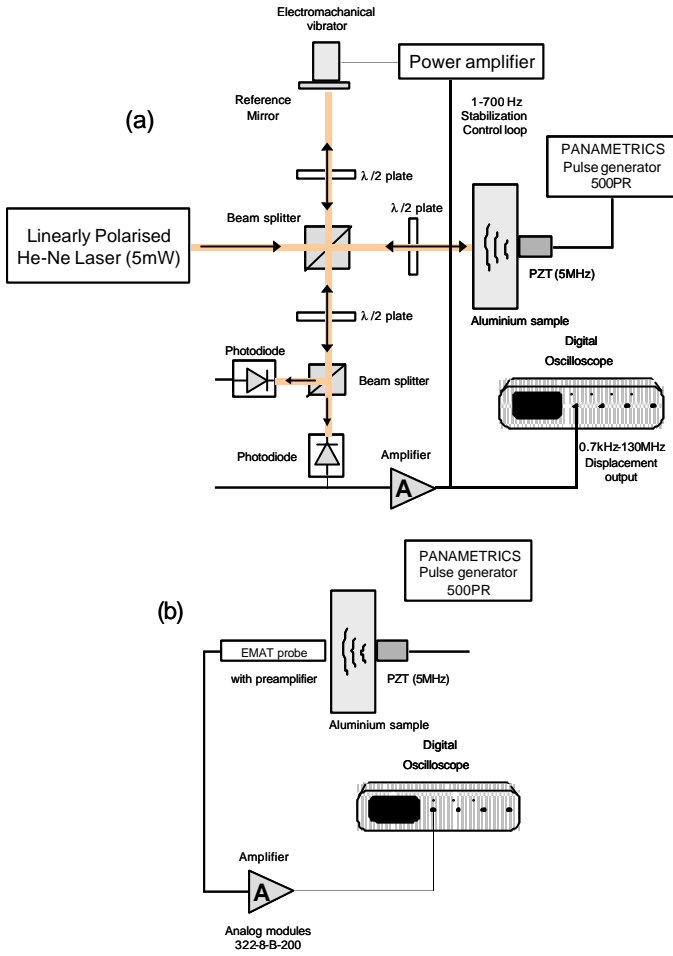


Figure 2(a) Schematic diagram of the modified Michelson Interferometer used to measure an absolute displacement of ultrasound in an aluminium sample. (b) The measurement arrangement used to perform cross-calibration with the EMAT using the same aluminium sample

[26] used in this work is shown in Figure 2(a). Ultrasonic pulses were generated in an aluminium sample by a 5MHz PZT transducer on the opposite side of a laser-irradiated side. A pulse generator (Panametrics 500PR) was used to provide a negative impulse signal to a PZT transducer.

A typical waveform for ultrasonic displacements in an aluminium sample detected by the interferometer is shown in Figure 3(a). In order to improve the signal-to-noise ratio, the averaging over 1024 detected signals was performed to derive this waveform. A voltage scale ($V(t)$) of received signals was converted to a displacement ultrasonic displacement ($d(t)$) scale by ([21]):

$$d(t) = \frac{1V(t)}{4pV_o} \quad (2)$$

where V_o is the maximum amplitude (peak-to-peak) of detected signals when an optical path length difference of the two optical beams is $\lambda/4$ and λ is a laser wavelength. The measurement of V_o was made when the interferometer was unstabilized, by disabling the feedback control loop. As expected, the ultrasonic arrival pattern is similar to the results

described in a previous section, except an in-plane shear wave arrival was not observed.

The outline of a cross-reference experiment to determine the absolute sensitivity of the EMAT is shown in Figure 2(b). Using the same aluminium sample and the same ultrasonic source from a PZT transducer, the EMAT was used to detect ultrasonic signals at the same point as the interferometer. Once again, a plastic film was used to ensure that the lift-off distance of the EMAT was constant for every experiment.

Figure 3(a)-(b) illustrates the first arrival longitudinal pulse obtained from the interferometer (dashed-line) and the EMAT (solid-line) on an expanded timescale. The pulse generator to the PZT was set at a high power output level without any

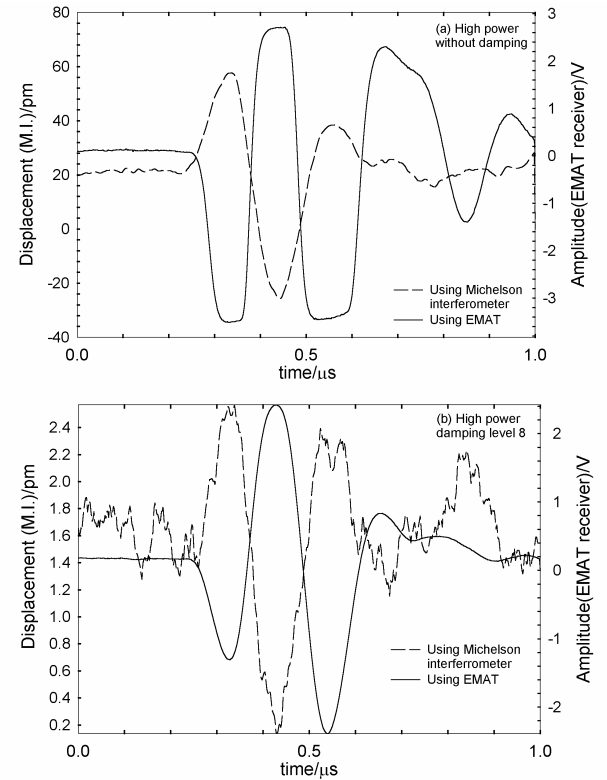


Figure 3(a) Comparison of the first arrival longitudinal pulse on an expanded timescale from a PZT transducer source using a Michelson interferometer (dashed-line) and the EMAT (solid-line). A pulse generator supplied a negative impulse to a PZT transducer was set as high power without any damping (b) with damping level of eight.

damping for the first calibration step. Typical waveforms obtained from both sensors are shown in Figure 3(a) on the same time scale. At this power level, the peak-to-peak ultrasonic displacement amplitude was about 83.4 ± 1.5 pm. For a typical waveform received by the EMAT, it is clear that saturation occurred at the amplifier output due to the high input signal. Therefore, the damping level of the PZT pulse generator was adjusted (increased) so that a received signal from the EMAT exhibited no amplitude saturation. This corresponded to a damping level of eight. Signals detected from both sensors were recorded at this power level. Comparison of these signals from both sensors is shown in

Figure 3(b). Despite a poor signal-to-noise ratio from the interferometer signal, a peak-to-peak ultrasonic displacement of 2.4 ± 0.5 pm was measured, equivalent to a peak-to-peak pressure of 167 ± 35 Pa. Using the corresponding peak-to-peak amplitude response of the EMAT, the absolute sensitivity of the EMAT was 1.98 ± 0.5 V.p m^{-1} .

It is also important to consider the noise-equivalent displacement together with the absolute sensitivity. This noise-equivalent displacement determines the minimum detectable displacement that a sensor detects on a single shot basis. A minimum detectable displacement is also useful when making a comparison with other ultrasonic receivers. Figure 8 presents a typical noise waveform from the EMAT (after amplified with the preamplifier and a commercial amplifier, Analog Modules 322-7-200). The vertical scale has been converted to a displacement scale using the absolute sensitivity of the EMAT of 1.98 V.p m^{-1} . The minimum detectable displacement of the EMAT was then estimated to be 1.0 ± 0.2 pm

IV. CONCLUSION

The design and characterisation of a highly sensitive miniaturised EMAT has been presented. A differential cascode preamplifier was designed and used to elevate small-induced voltages from the pick-up coil. A series of experiments was performed to characterise the EMAT and assess its performance. The frequency response of the EMAT was found to vary when performed measurements using aluminium and PMMA samples. The centre frequency and bandwidth of the EMAT and the preamplifier were 4.02 and 7.50 MHz, respectively, when using aluminium samples. The EMAT was also cross-calibrated with an absolute out-of-plane displacement measured by a Michelson interferometer. The resulting absolute sensitivity of the EMAT was 1.98 ± 0.5 V.p m^{-1} for longitudinal waves. The minimum detectable displacements of the EMAT were about 1.0 ± 0.2 pm. These figures are at least a 15-folded more sensitive than previous designs reported in the literature.

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