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Enhancement of signal amplitude of surface wave EMATs based on 3-D simulation analysis and orthogonal test method

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ABSTRACT

The amplitude of an ultrasonic signal generated by electromagnetic acoustic transducers (EMATs) is typically low when compared to those generated by contacting transducers, which restricts the application of EMATs in the fields of nondestructive testing and nondestructive evaluation. The transmission process of a surface wave EMAT is studied, based on a previously established 3-D model, with the aim of enhancing the amplitude of ultrasonic waves generated by the EMAT. The effect of changing various EMAT parameters on the surface wave is investigated, by utilizing the orthogonal test method. Results indicate that after optimization, the signal amplitude of the EMAT has increased by 25.2%.

1. Introduction

Electromagnetic acoustic transducers (EMATs) are a type of non-contact, ultrasonic transducer, capable of generating or detecting ultrasonic waves. They can be particularly attractive for some applications in nondestructive testing (NDT) and nondestructive evaluation (NDE), requiring no liquid couplant, having the flexibility to generate and detect multiple wave modes, with the capability of operating on hot or moving components [1,2].

The ultrasonic wave amplitude excited by EMATs is usually very weak compared with that of the piezoelectric transducers, as the generation mechanisms are relatively inefficient. In practice, one attempts to compensate for the poor generation efficiency by maximizing transmitting power, often using narrowband and ultra-low noise receivers, and by introducing various signal processing methods [3], which inevitably increases the complexity and the cost of EMAT-inspection systems. Researchers have simulated and analyzed the working processes of EMATs, based on various physical models and have performed extensive investigations of the EMAT mechanisms [3–11], in an attempt to reduce the issues associated with their low efficiencies. This previous work has extended the understanding of EMATs' operation principles, laying the foundation for the improvement of EMAT performance.

The excitation of ultrasound generated by an EMAT is a multi-physics process, which involves the interaction of eddy currents, static and dynamic magnetic fields and the sample. To facilitate analysis, previous work has typically established simplified EMAT models, based on several preconditions, including using 2-D models to represent 3-D situations, assuming the static magnetic field is uniform, neglecting some of the influence of dynamic magnetic fields, or building models only for the intermediate working process of EMATs [3–10]. Based on these simplified models, researchers have previously studied the influence of a few EMAT parameters (such as lift-off distance, magnet-to-coil width ratio) on the amplitude of the ultrasonic signal and have enhanced the ultrasonic amplitude merely by improving the intermediate physical fields, including the eddy current, magnetic fields or Lorentz force fields, of the transmission processes of EMATs [3–10]. To date, however, there has been little work studying the method of enhancement of ultrasonic amplitude, by investigating and comparing the influence of various EMAT parameters on the amplitude, with a holistic approach considering the EMAT's transmission process as a whole.

A novel 3-D modeling method has recently been proposed, for the meander-line-coil surface wave EMATs operating on aluminum plates [11]. The accuracy and integrity of the model have been significantly improved, modeling a more complete transmitting process of the surface wave EMATs, with consideration of the influence of the dynamic magnetic fields on the generation process. This paper presents an improved and extended study of the influence of various EMAT parameters on the amplitude of

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generated ultrasonic waves, and proposes an approach for surface wave EMATs to enhance their signal amplitude. This paper is organized as follows: firstly, the transmission process of a surface wave EMAT is studied, based on the simulation of a 3-D model; secondly, using the orthogonal test method, the influence of various parameters on EMAT generated ultrasonic wave amplitude is obtained, and these parameters are optimized to maximize the wave amplitude; and finally, experiments are conducted to validate the results of the proposed method.

2. 3-D simulation analysis

Surface wave EMATs have been used widely for the inspection of the surface and subsurface layers of samples. To excite large amplitude surface waves with high directivity, a surface wave EMAT usually consists of a meander-line coil and a vertical static magnetic field, either from permanent magnets or from an electromagnet. As the sample under test is involved in the energy conversion process, it is also effectively, part of the transducer. Generally speaking, three mechanisms are responsible for the electro-acoustic transduction of EMATs: the Lorentz force, the magnetostrictive force and the magnetization force [12]. In aluminum, the Lorentz force is the only generation mechanism that one needs to consider for EMATs.

The generation process of a surface wave EMAT on an aluminum plate is illustrated in Fig. 1, where X, Y and Z are axes of the Cartesian coordinate system. When an alternating current J_c travels through the meander-line coil, a dynamic magnetic field $B_{d,m}$ is generated in the electromagnetic skin depth of the aluminum plate. The time varying magnetic field induces eddy current J_E within the skin depth of the plate, and the electrons that constitute this eddy current experience Lorentz forces $f_{L,d}$ and $f_{L,s}$, when the eddy current J_E interacts with the dynamic magnetic field $B_{d,m}$ from the EMAT coil and the static magnetic field B_s (from a magnet) respectively. The directions of these forces are shown in Fig. 1. The electrons that experience these Lorentz forces scatter off the atoms, exchanging momentum with the atoms. This in turn gives rise to the coherent motion of the aluminum atoms, leading to the generation of an ultrasonic wave. In this case, we are interested in the resultant wave mode that propagates along the surface layer of the plate. The reception of ultrasonic waves by an EMAT is sometimes described as the reverse process of the generation mechanism, but this is not strictly true. In detection, when the atoms and free electrons in the metal move due to the displacement associated with an ultrasonic wave, the free electrons with energy above the Fermi level will experience a Lorentz force in the presence of a magnetic field. These electrons constitute a current, that will generate a magnetic field, which when within the electromagnetic skin depth of the surface will produce a magnetic field external to the sample that can induce an electromotive force (voltage) on a suitably orientated detection coil.

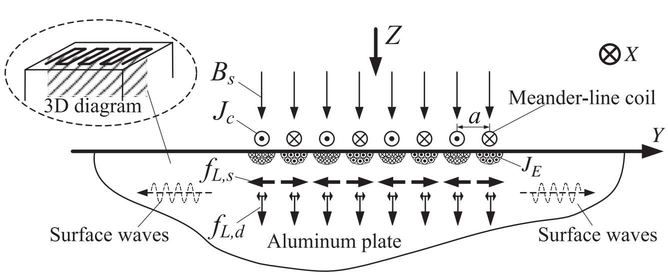

Fig. 1. Working process of surface wave EMAT on aluminum plate.

Based on our previously published modeling method [11], a 3-D model is established for a surface wave EMAT operating on an aluminum plate. The physical model of the transducer is shown in Fig. 2a, which consists of a coil, a neodymium–iron–boron (Nd–Fe–B) magnet, an aluminum plate and surrounding air, all of which is surrounded by a boundary that acts so as to produce the effect that the model extends spatially to infinity and still remains stable and convergent. This boundary is sometimes referred to as an infinite field. The coil, the plate, the coordinate system, and the positive direction of the transmitting current are shown in Fig. 2b, where the origin O is on the upper surface of the plate, under the center of the coil. The propagation velocity c of surface waves in aluminum plates is assumed to be 2930 m/s. The coil has 6 turns of conductors and the spacing interval a between the conductors is 2.93 mm; each conductor is 35 mm long, 1.0 mm wide and 0.05 mm thick with lift-off distance from the sample of 0.5 mm. The spatial periodicity of the EMAT coil corresponds to the dominant spatial frequency of the generated surface wave of 5.86 mm, such that the frequency of this dominant wavelength is $f = c/\lambda = 500$ (kHz). The drive current for the EMAT is matched to this frequency. The dimensions of the magnet are $40 \times 40 \times 15$ mm, and the magnet has remanant magnetism of 1.21 T, coercive force of 899 kA/m and maximum magnetic energy product of 279 kJ/m^3. In practice, the magnet is shielded to prevent the generation of ultrasound in the magnet, and the lift-off between the magnet and the coil is set to 2 mm. To increase the calculation efficiency, only the region of the plate where the transduction process takes place is modeled. The dimensions of the modeled plate are $70 \times 70 \times 1.4$ mm, and its electrical conductivity is 2.6×10^{-8} Ω m. The transmitting current is a 6-cycle tone burst signal with peak-to-peak value of 100 A.

The distribution of eddy current, magnetic fields, Lorentz forces and surface waves on the aluminum plate can be obtained by solving the model [11]. Assuming $f_{L,sX}, f_{L,sY}, f_{L,sZ}$ and $f_{L,dX}\, f_{L,dY}\, f_{L,dZ}$ are the components of $f_{L,s}$ and $f_{L,d}$ in X, Y, and Z directions respectively, the distribution of the six components is shown in Fig. 3, which illustrates that both of the Lorentz forces chiefly distribute along the outline of the coil, and $f_{L,s}$ is stronger than $f_{L,d}$ under the given condition; $f_{L,d}$ mainly acts in the Z direction and

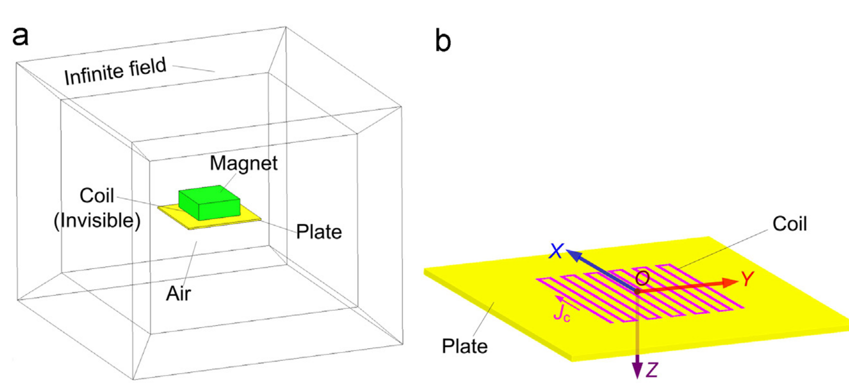

Fig. 2. The 3-D physical model of surface wave EMAT. (a) Whole model and (b) Model of coil and plate.