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Induction coil as a non-contacting ultrasound transmitter and detector: Modeling of magnetic fields for improving the performance

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ABSTRACT

A simple copper coil without a voluminous stationary magnet can be utilized as a non-contacting transmitter and as a detector for ultrasonic vibrations in metals. Advantages of such compact EMATs without (electro-)magnet might be: applications in critical environments (hot, narrow, presence of iron filings...), potentially superior fields (then improved ultrasound transmission and more sensitive ultrasound detection).

The induction field of an EMAT strongly influences ultrasound transduction in the nearby metal. Herein, a simplified analytical method for field description at high liftoff is presented. Within certain limitations this method reasonably describes magnetic fields (and resulting eddy currents, inductances, Lorentz forces, acoustic pressures) of even complex coil arrangements. The methods can be adapted to conventional EMATS with a separate stationary magnet.

Increased distances (liftoff) are challenging and technically relevant, and this practical question is addressed: with limited electrical power and given free space between transducer and target metal, what would be the most efficient geometry of a circular coil? Furthermore, more complex coil geometries ("butterfly coil") with a concentrated field and relatively higher reach are briefly investigated.

1. Introduction

Magnetic fields are utilized in electromagnetic acoustic transducer (EMAT) schemes for ultrasound excitation and detection in metallic test objects [1]. The application is ultrasound testing of metallic work pieces with a non-contacting and non-destructive method. As an inherent advantage the magnetic fields permeate most dielectric barriers (air, humidity, dirt, plastic foil...) and exclusively interact with the metallic target.

A practical disadvantage is that the achieved transduction efficiencies and ultrasound intensities are quite modest with respect to contacting PZT transducers. The efficiency even strongly decreases with increasing gap (=liftoff g) between the metal surface and EMAT; therefore, in practical applications, the g is usually smaller than a few mm.

Conventional EMATs consist of an RF inductor coil and a permanent magnet. The permanent magnet projects a DC magnetic flux density B_0 toward the target metal. The RF inductor induces eddy currents in the metal surface, and together with B_0, Lorentz forces or pressures at RF frequencies are experienced in the metal, resulting into ultrasound transduction. A conventional EMAT with permanent magnet also works as an ultrasound detector.

The conversion efficiency between electrical excitation power and achieved ultrasound intensity scales with the locally (at and in the metal surface) present B_0^2 [2], which is proportional to the local energy density of the permanent field B_0. Also the sensitivity of an EMAT as an ultrasound detector scales with B_0^2. On the basis of conventional magnets, it is quite difficult to achieve magnetic flux densities toward or even higher than 1 T over certain distance g into the metal target. Practically very relevant, this limits the conversion efficiency, the overall sensitivity and, in particular, the effective range of EMAT techniques.

In an even simpler transmitter scheme, an RF induction coil alone—without a permanent magnet—can also excite ultrasound vibrations in a distant metallic target. Here, the dynamic field B_{RF} from the induction coil (at RF frequencies), together with the induced eddy current (being proportional to the dynamic field B_{RF}), produces RF Lorentz forces and ultrasonic vibration [3–8]. Therefore, the Lorentz forces or effected RF pressures are proportional to ${B_{RF}}^2$. It has been known for a long time [3,4,8] that this quadratic relation has several consequences: the Lorentz forces and pressures are exclusively repulsive (unipolar), and they oscillate with a doubled RF frequency. In addition, the dynamic field B_{RF} cannot permeate into the depth of the metal target. Thereby

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the in-plane field component of a dynamic field is increased with respect to a stationary field with same excitation currents. This field deformation ("field compression") influences the Lorentz forces: the out-of-plane forces are increased and the in-plane forces are reduced with respect to a conventional EMAT with stationary field. It can be shown (paragraph 7 in the supplement) that with a limited amount of total magnetic energy (energies of stationary and dynamic field together) the achieved ultrasound intensity with just an RF field and without a stationary field is actually maximal. It is however a practical problem to provide high magnetic energies at RF frequencies. Undoubtedly, a strong NdFeB permanent magnet with just a "cold" DC field is more convenient.

Without stationary magnet, the excited ultrasound intensity scales with the square of the RF pressures and is proportional to $B_{RF}{}^4$. In other words, the excited ultrasound power increases with the square of the electrical power in the RF induction coil. The relation holds as long as the excited ultrasonic power is much smaller than the electrical power and this restriction is usually fulfilled: the conversion efficiency for MHz ultrasound typically is much lower than 1%.

With sufficiently high excitation power, a simple induction coil can provide magnetic flux densities B_{RF} significantly above 1 T, more than the stationary field in a conventional EMAT. In addition, as inherent advantage, the B_{RF} implicitly displays geometrical overlap with the induced eddy currents in the target metal. Thus, relatively high acoustic pressures are achieved and relatively strong ultrasound signals can be transmitted [3,9].

It is repeatedly noted as a substantial weakness of a "coil only EMAT" without an additional and stationary field that it cannot detect ultrasound vibrations [3,4,6,8]. This is true for a *passive* coil. The problem can be overcome by using an *active* coil as a *receiver* and this concept is briefly demonstrated here. It should however be noticed that this topic is not intended as the main purpose of this contribution, nor shall this demonstration be understood as a fully developed design.

Fig. 1 describes an experimental proof of concept for ultrasound transmission and ultrasound detection via two non-contacting "coil only EMATS". Two practically identical spiral coils L_1 and L_2 with 5 windings each were made from 1 mm copper wire. The outer radius of the spirals is 20 mm. No ferromagnetic material or permanent magnet is involved. The central element is an aluminum rod (70 cm length, 20 mm diameter), which serves as a delay line for an ultrasound transmission. In such basic experiments, a defined delay is helpful for a clear separation between initial signal artifacts and true ultrasonic signals. The coils are positioned close – but non-contacting – to the plane endings of the aluminum rod; the air gap g between coils and rod is chosen to approximately 1 mm.

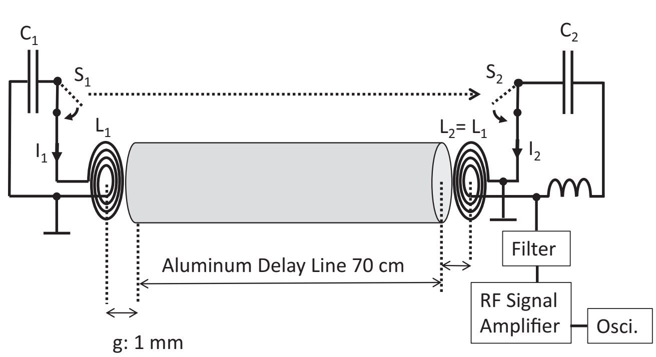

Fig. 1. Two identical coils L_1 and L_2 ("copper only") are demonstrated as contactless ultrasound transmitter (left arrangement, similar to [9]) and ultrasound detector (right arrangement) at MHz frequencies. For ultrasound detection, L_2 is activated with a strong and relatively prolonged (typ. 1 ms) current pulse I_2 from C_2. The detected signal (MHz) then can be tapped from L_2. Potentially stronger fields with a more suitable topology can be achieved for the detector L_2.

The capacitor C1 is charged to 12 kV and, when switch S_1 fired, a pulsed and strong RF current I_1 excites the inductor L_1, well approaching 10 kA for a few µs. This scheme transmits a strong ultrasonic pulse into the delay line, as already described in much more detail and readily available for the interested reader [9]. Here the frequency of the LC-circuit L_1 and C_1 was 700 kHz and thus, the characteristic frequency of the transmitted ultrasound was 1.4 MHz.

The coil L_2 at the other ending of the delay line is connected to a similar circuitry. The solid state switch S_2 (an IGBT battery) is instantaneously triggered by S_1 or I_1. Then capacitor C_2 starts to discharge into L_2. C_2 is chosen much bigger (35,000 µF) than C_1 (150 nF) and the voltage is much lower (25 V). Therefore the discharge current I_2 rises much slower (≈100 µs) and lasts much longer (≈1 ms) than I_1. From the discharge characteristics it can be derived that the magnitude of I_2 approaches 2 kA. Then L_2 produces a magnetic flux density (compare [9], more calculus below) within the gap g in the order of 2 T. This is stronger than available from even voluminous permanent magnets and furthermore, that field from L_2 is spatially matched to the eddy current sensitivity of L_2. The pulsed L_2 clearly repels metals (magnetic pressure), even ferromagnetic iron and steel is rejected. Only non-conducting and ferromagnetic material (ferrite, iron powder cores) is attracted by L_2.

During this relatively long current pulse I_2 an additional RF signal can be tapped from L_2. That RF signal was guided through a simple filter element and – after some impedance transformation and amplification – was available for the oscilloscope.

Clearly an RF burst after 110 µs and at about 1.4 MHz is observed in the oscilloscope. 110 µs equals the traveling time of sound through the 70 cm aluminum rod. That RF signal at 1.4 MHz strongly decreases, when either retracting L_1 or L_2 from the aluminum endings. An additional echo after 340 µs (ultrasound pulse traveling for, back, and for again) is observable. The signals are quite similar to those already presented in [9] and besides multiple echoes, also distinct longitudinal propagation modes from the aluminum rod are observable [9,10]. The signal's raw amplitude – before amplification – was about 40 mV and this is not a small effect for an EMAT. The observed 1.4 MHz signal completely disappears when suppressing I_2.

The signal amplitude is proportional to I_2, or: the signal energy at a given ultrasonic vibration (=conversion efficiency) is proportional to the field energy B^2, as in conventional EMATs. The *transmitted* ultrasound from the L_1 (left) however scales with B^4 [3,4,9]. There is a difference between transmitting and receiving ultrasound. Nevertheless, it is out of the question that the activated L_2 as a "copper only EMAT" has become a non-contacting detector for MHz ultrasound.

When – instead of releasing the pulsed current I_2 – attaching a reasonably shaped NdFeB permanent magnet to the back side of L_2, the detector coil works like a conventional EMAT with a static field. Then however, in direct comparison, the received signal amplitude is notably weaker: instead of 40 mV with I_2 only 6 mV is obtained with the NdFeB magnet. Although the NdFeB design certainly could be more optimized, it is not likely that the principal efficiency of the "copper only" system L_2 and I_2 as a *detector* (which also can be more optimized) can be reached with such separate and conventional magnet: the inherent advantage of the "copper only system" is the geometrical match between excitation field and sensing of eddy currents, together with stronger magnetic fields. An additional enhancement – besides an optimized coil geometry and strong I_2 – could be achieved by a ferrite back plate [7] or perhaps by an iron powder back plate (higher saturation toward ≈ 2 T). Such back plates are not intended as permanent magnets but they