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Optimal Impedance on Transmission of Lorentz Force EMATs

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Abstract. Electromagnetic-acoustic transducers (EMATs) are attractive for non-destructive inspections because direct contact with the specimen under test is not required. This advantage comes at a high cost in sensitivity and therefore it is important to optimise every aspect of an EMAT. The signal strength produced by EMATs is in part determined by the coil impedance regardless of the transduction mechanism (e.g. Lorentz force, magnetostriction, etc.). There is very little literature on how to select the coil impedance that maximises the wave intensity; this paper addresses that gap. A transformer circuit is used to model the interaction between the EMAT coil and the eddy currents that are generated beneath the coil in the conducting specimen. Expressions for the coil impedances that satisfy the maximum efficiency and maximum power transfer conditions on transmission are presented. To support this analysis, a tunable coil that consists of stacked identical thin layers independently accessed is used so that the coil inductance can be modified while leaving the radiation pattern of the EMAT unaffected.

INTRODUCTION

Electromagnetic-acoustic transducers (EMATs) do not require direct contact with the specimen under test [1, 2, 3, 4]. This is an important advantage over standard piezoelectric transducers which have to be used with coupling agents. However, EMATs produce much weaker signals and therefore understanding how the elements of their design can be improved is important.

Regardless of the transduction mechanism (e.g. Lorentz force, magnetostriction, etc. [2]), the impedance of the coil of the EMATs plays an important role in increasing the strength of the signal. When reviewing the scarce literature on this subject [5, 6, 7, 8], the tendency is to build coils by trial and error and then design a matching network so that the driving source transfers the maximum power to the coil.

However, with this approach, there may be no control of how much power goes to the coil resistance and how much to the eddy currents generated in the specimen beneath the coil. Nor is there any guarantee that the eddy currents are being maximised or enough theoretical or experimental understanding of how a certain configuration is affected by frequency or coil lift-off from the specimen. This is important because the intensity of the ultrasonic waves increases with the intensity of the eddy currents when using Lorentz force EMATs, which was found to be the predominant transduction mechanism in steel [9]. Moreover, matching networks could introduce losses and parasitic capacitance that degrade the performance of the system. They may also overcomplicate the design, affect the bandwidth and require extra components which could be less convenient in some applications.

Intuitively, coils with a high inductance will produce a better coupling between the EMAT coil and the eddy currents. However, the higher the inductance of the coil the lower the current that can flow through it. Conversely, a low inductance allows higher currents to flow through the coil but, because of poorer coupling between the coil and the eddy currents, most of the power is dissipated in the coil and driver resistance rather than in the eddy currents. For these reasons there is a clear need to study how the coil impedance affects the power transfer to the eddy currents.

This problem is very similar to that faced in inductive coupling energy transfer [10, 11, 12] and radio frequency identification [13, 14] systems, where one transmit coil transfers energy to a receive one through inductive coupling. In these fields most of the effort has been placed in maximising the efficiency of the energy transfer; however, in EMATs maximum power transfer is more desirable than maximum efficiency. This is because the highest signal-to-noise ratio is achieved in the shortest period of time.

In this paper a transformer circuit is employed to model the interaction between the EMAT coil and the eddy currents that appear in the conductive specimen beneath the coil. A variation of this model has been employed to study the impedance of the coils in eddy current testing techniques [15, 16]. Starting from this model, the optimal electrical configurations and coil impedances that produce the highest power transfers to the eddy currents and the maximum efficiencies (i.e. the maximum ratio of the power dissipated by the eddy currents with respect to all loads) on transmission are studied. To support this analysis, a tunable coil that consists of stacked identical thin coil layers independently accessed is introduced so that the overall coil inductance can be modified while leaving the radiation pattern of the EMAT unaffected.

The organisation of this document is as follows: first the EMAT transduction principles and the electrical transformer circuit to model the interaction between the EMAT coil and the eddy currents are introduced. Following this, the optimal coil impedance and electrical configuration for maximum efficiency and power transfer to the eddy currents are investigated. Using a tunable coil, experiments are conducted to show how these optimal conditions change with frequency and the coil lift-off from the specimen. Finally, conclusions are drawn.

BACKGROUND

EMAT Transduction Mechanism

EMATs consist of a coil that carries alternating current and a bias magnetic field such as that produced by permanent magnets. One of the most used configurations is shown in Fig. 1, it comprises a single cylindrical permanent magnet placed on top of a pancake-like coil.

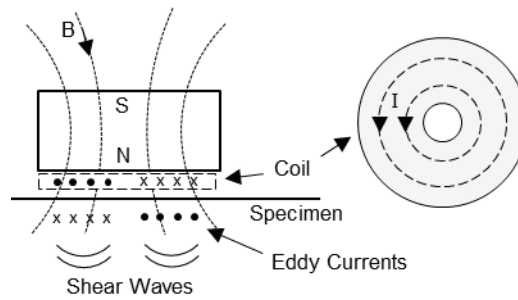


FIGURE 1. EMAT with a cylindrical magnet on top of a pancake coil.

First, the coil induces eddy currents in a conductive specimen whose path tends to mimic that of the coil. Then, these eddy currents with density $\mathbf{J}_e$ interact with the bias magnetic field of the permanent magnet with flux density $\mathbf{B}$ and a Lorentz force density results on the charged particles (electrons) [1, 2]

$$\mathbf{f} = \mathbf{J}_e \times \mathbf{B}. \quad (1)$$

The charged particles interact with the atomic structure of the material which causes deformations that generate ultrasonic waves. Note that the intensity of the generated ultrasonic waves increases with the intensity of the eddy currents. There are other generation mechanisms for EMATs such as magnetostriction, but in steel, the main focus of this paper, the Lorentz force was found to be the predominant one [9].

Coil and Eddy Current Transformer Model

The interaction of the EMAT coil and the eddy currents on transmission is modelled using the transformer circuit of Fig. 2. Variations of this model have been widely employed for eddy current testing in the past [15, 16].

A series of simplifications are now imposed to the problem. Firstly, the effect of the eddy currents in the magnets on top of the coils is disregarded. The reason being that these currents could be attenuated by, for example, fragmenting the magnet to increase the resistance of the eddy current path or increasing the distance between the magnet and the coil. Hence they will be small and their contribution can be ignored. Secondly, the parasitic capacitance of the coil, cable and driving source is not considered. This is a reasonable assumption within the frequency range of interest for

this paper (less than 3 MHz). Radiation and hysteresis losses are not considered either; this is because the coupling and losses of the eddy currents are dominant. Finally the coil resistance and the driver resistance are both modelled as a single resistor R_c for mathematical convenience – this is possible because they are connected in series.

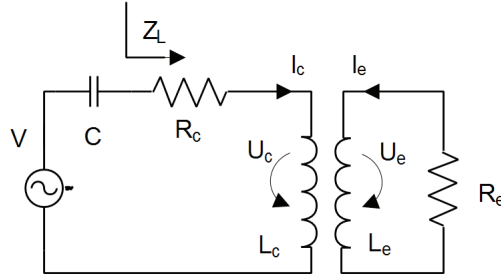


FIGURE 2. Transformer circuit for modelling the interaction of the EMAT coil and the eddy currents on transmission.

In the circuit of Fig. 2 R_e is the resistance of the eddy current path. The voltage at both sides of the transformer, i.e. at the inductors representing the EMAT coil and the eddy currents with inductances L_e and L_c respectively, can be found as

$$\begin{bmatrix} U_c \\ U_e \end{bmatrix} = j \begin{bmatrix} X_c & X_M \\ X_M & X_e \end{bmatrix} \begin{bmatrix} I_c \\ I_e \end{bmatrix} \quad (2)$$

where $X_e = \omega L_e$, $X_c = \omega L_c$, $X_M = k \sqrt{X_c X_e}$, ω is the angular frequency, j the imaginary unit, and $k \in [0, 1]$ is the coupling factor between the coil and the eddy currents. There are an ideal voltage source V and a capacitor C connected in series with the coil; the capacitor will be used to compensate the reactive component seen by the source.

OPTIMAL COIL IMPEDANCE ON TRANSMISSION

There are two main optimal electrical conditions regarding the transfer of energy between the driving source and the load: maximum efficiency and maximum power transfer. In the case of the EMAT coil, the maximum efficiency is obtained by maximising the ratio between the power dissipated by the eddy currents and all the loads (including the eddy currents); this is critical for energy limited devices such as those that run on batteries. The other condition maximises the power dissipated by the eddy currents, which is the fastest way to produce a desirable signal-to-noise ratio – which is often preferred in NDE measurements.

Maximum Power Transfer

The power dissipated by the eddy currents can be expressed as (see model of Fig. 2)

$$P_e = \frac{|I_e|^2 R_e}{2} \quad (3)$$

where I_e is the peak value. After some manipulation this yields

$$P_e = \left| \frac{V}{R_c + jX_c - jX_{Cp} + \frac{X_M^2}{Z_e}} \right|^2 \left| \frac{X_M}{Z_e} \right|^2 \frac{R_e}{2}. \quad (4)$$

where $X_{Cp} = \frac{1}{\omega C}$ is the capacitor reactance and $Z_e = R_e + jX_e$.

If X_{Cp} is chosen so that the complex components in the denominator cancel out at ω_0 , P_e increases and equation (4) can be simplified to

$$P_e = \frac{V^2}{2 \left(\frac{R_c |Z_e|}{X_M \sqrt{R_e}} + \frac{X_M \sqrt{R_e}}{|Z_e|} \right)^2}. \quad (5)$$

To further increase P_e the denominator of (5) can be minimised. First let us assume that the shape of the eddy currents does not change, i.e. R_e and L_e remain constant, as well as k for a given ω_0 . Hence, since $R_c > 0$ (because of the driver resistance) and R_c is a monotonically increasing function of L_c for a given ω_0 (due to the coil resistance), the denominator has to be a convex function. So there is an optimal value of L_c such that P_e reaches its maximum – note that $X_M = \omega_0 k \sqrt{L_e L_c}$.

To simplify the analysis, let us assume that R_c can be considered a constant when L_c varies due to changes in the number of turns of the coil. This is a reasonable approximation since the output impedance of an amplifier is in many cases a few tens of ohms whereas the impedance of a coil (this is in air without the effect of the eddy currents taken into account) is just a few ohms. Hence by differentiating (5) with respect to X_M , it reaches its maximum when

$$L_c = \frac{R_c (R_e^2 + \omega_0^2 L_e^2)}{\omega_0^2 k^2 R_e L_e}. \quad (6)$$

It should be noted that in practice it may happen that the resistance of the coil is comparable to that of the driver and therefore R_c cannot be considered constant when changing L_c which leads to a different expression for the optimal L_c . Moreover, regardless of the restrictions on R_c , it may also occur that the optimal L_c is either too small or too big in order to be practically built while leaving R_e , L_e and k constant for a given ω_0 . Notwithstanding all this, the previous approach provides a useful insight into the problem.

When equation (6) is substituted back into equation (5), it yields

$$P_{e,max} = \frac{V^2}{8R_c}, \quad (7)$$

which is the maximum power dissipated by both the eddy currents and the coil and driver resistances under the maximum power transfer condition.

It should be noted that the maximisation of the eddy current power (3) is equivalent to simply maximising the eddy current I_e , as explicitly stated in equation (1), for a given eddy current resistance R_e . However, the use of (3) is sounder from the electrical point of view and simplifies equations. The final step in maximising I_e is to combine equations (3) and (7)

$$|I_e| = \frac{V}{2\sqrt{R_e R_c}}. \quad (8)$$

This formally confirms the intuitive result that under maximum power transfer condition I_e increases by decreasing R_c and R_e for a given V .

This suggests that in the case where only a certain region of the coil/eddy current path is used to generate the active ultrasonic aperture based on the Lorentz force, once an optimal coupling has been achieved the remaining section of the coil/eddy current path should be designed such that they have the lowest resistances. This basically means that excessively large non-active sections of coil should be avoided. This conclusion should hold regardless of whether equation (6) accurately corresponds to the optimal value of L_c .

Maximum Efficiency

The efficiency of an EMAT coil is computed as the ratio between the power dissipated by the eddy currents P_e and all the loads (including P_e)

$$\eta = \frac{P_e}{P_e + P_c} \quad (9)$$

where P_c is the power dissipated by the coil-driver resistance R_c . It can be shown that

$$\eta = \frac{1}{1 + \frac{R_c}{k^2 X_c} \left(\frac{R_e}{X_e} + \frac{X_e}{R_e} \right)}. \quad (10)$$

From this expression it can be concluded that to maximise efficiency, k should be maximised as well as the ratio $\frac{X_e}{R_e}$, which is basically the quality factor of the coil and driver combined.

RESULTS

Two experiments were conducted to support the theoretical results from the model. First, the effect on the signal amplitude when using a series capacitor between the driving source and the EMAT was investigated over a reasonable frequency range. Secondly, a tunable coil was introduced to investigate its optimal impedance for maximum power transfer condition. Then the changes of the signal amplitude were studied when lift-off and frequency change.

Impact of Series Resonance on the Signal Strength

The use of a resonant series capacitor increases the power delivered to the load by cancelling out the reactive components seen by the driving source; this is a basic concept of resonance shown in equations (4) and (5). This tuning procedure is a necessary step in the process of finding the impedance of the coil that satisfies the maximum power transfer condition. In the following experiment the effect of resonance on the signal strength is quantified for a given EMAT design.

Two identical EMATs with pancake-like coils were arranged at opposite sides of a steel specimen with a thickness of 40 mm. Each EMAT comprises a two layer coil with 26 turns per layer and an overall coil thickness of 0.5 mm with inner and outer diameters of 10 and 30 mm. A cylindrical Neodymium-N42 magnet [17] with diameter and height of 30 and 20 mm respectively was placed on top of the coil with a 2 mm gap in between. These EMATs generate a shear wave with radial polarisation similar to that used in [18].

The transmit EMAT was connected in series with a 1 nF capacitor as shown in the model of Fig. 2. The value of the capacitors was chosen so that, when placed on top of the steel sample with no lift-off, a purely resistive impedance of 40 Ohm appeared at the coil terminals at roughly 1 MHz. This 40 Ohm value, though arbitrary, is known to be easily handled by standard driving sources. The impedance value was confirmed by using an impedance analyser (SinePhase Z-Check 16777k, SinePhase Instruments GmbH, Hinterbruehl, Austria); the resulting admittance curves are shown in Fig. 3.

The behaviour of a series resonant system can be better understood by using admittance curves rather than impedance ones. It can be observed how the system resonates at roughly 950 kHz with a real admittance of approximately 25 mS (40 Ohm). At this point the current through the circuit reaches a maximum (assuming a purely resistive source). This impedance profile should accommodate tone-bursts excitations with more than 3 cycles whose bandwidth at 1 MHz is roughly 0.4 MHz.

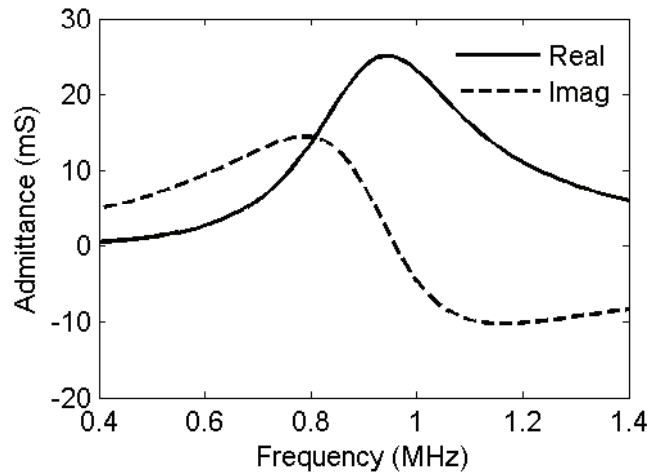


FIGURE 3. admittance curves for the pancake-coil EMAT on steel with a series capacitor of 1 nF and a lift-off of 0 mm.

The transmit EMAT was connected to the driver output of a WaveMaker-Duet system (custom made for the NDE group of Imperial College London). The driver of the system was set to generate a 4-cycle tone-burst tapered with a Hann-like window using a maximum amplitude of 40 Vpp at 1 MHz. The series capacitor was not connected during this operation. A derivation of the driver output was connected to an oscilloscope (LeCroy WaveRunner 44Xi) through

a high impedance buffer in the WaveMaker-Duet system, so that this reference could be used to read the driver output voltage without affecting the load.

The receive EMAT was connected to a 60 dB gain pre-amplifier in the WaveMaker-Duet system and its output to one channel of the oscilloscope. The driver trigger output of the WaveMaker-Duet system was also connected to another channel of the oscilloscope. Then the central frequency of the tone-burst was varied from 0.4 to 1.4 MHz in steps of 50 KHz. By inspecting the signal it was confirmed that no saturation of the driver occurred. Received signals for each central frequency were synchronised with the driver trigger output and averaged 4000 times to increase the SNR above 40 dB. The maximum voltage recorded was in the range of tens of millivolts. The results were normalised to the maximum measured value since the purpose of the experiments was to compare different configurations and the absolute voltage measured is dependent on the instrumentation used.

Then the envelope of the signal was extracted by means of the Hilbert transform. The results with and without the series capacitor connected to the driver are plotted in Fig. 4. The vertical axis shows the peak amplitude of the envelope for each frequency tested within the range. The fact that the curves are not smooth suggests there is still some source of noise or error affecting the results, for example when detecting the peak amplitude.

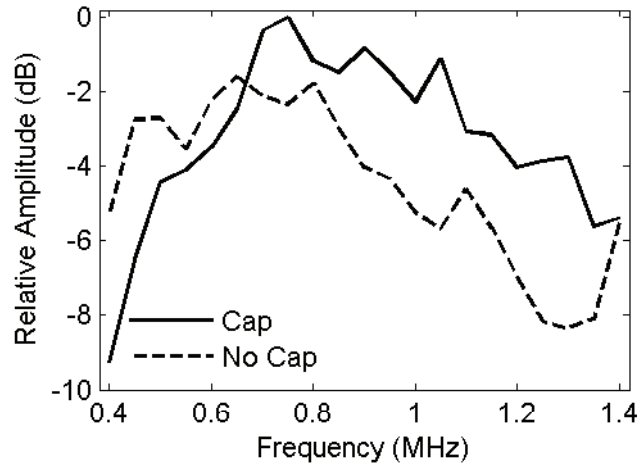


FIGURE 4. Effect of series resonant on transmission.

The main observation is that the amplitude of the signal increases within the frequency range from 0.7 to 1.4 MHz when the series capacitor is connected. However, for this particular example the improvement is generally no bigger than 3 dB. Note that the highest amplitudes occur near 0.75 MHz, which is not necessarily the resonant frequency of the driver-coil, other factors such as the change in the EMAT radiation pattern with frequency may have a stronger influence in the amplitude of the signal within this frequency range.

Optimal Number of Turns for Maximum Power Transfer

A coil was constructed by stacking identical thin coil layers as shown in Fig. 5. By using this coil the shape and therefore the impedance of the eddy current path does not change, but the impedance of the coil can be modified by choosing a different number of layers. This allows the maximum power transfer condition to be investigated.

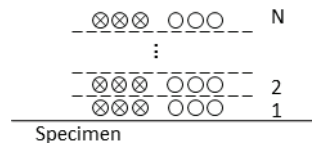


FIGURE 5. Cross-section of a multilayer coil with magnet on top.

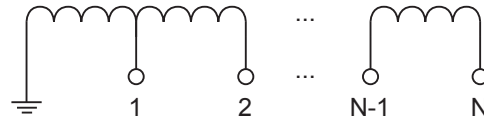


FIGURE 6. Equivalent electrical circuit of multilayer coil showing the connexion of the terminals to the layers.

The equivalent electrical circuit of the multilayer coil is simply a set of coils connected in series as sketched in Fig. 6, where each layer can be accessed independently. So if, for example, two layers are found to perform best, only terminal 2 is connected while the rest are left open. The unconnected layers will not affect the results because no current flows through them. Note that the inductance of the coil is not necessarily the sum of the individual layer inductances due to the mutual coupling between the layers. The thickness of this multilayer coil must be kept to a minimum, otherwise the farthest layers from the specimen will be poorly coupled to the sample, and the condition requiring the coupling factor k being constant will not be satisfied. For this reason it was convenient to build the coil using multilayer printed circuit board technology.

A 5-layer butterfly coil was built using a layer thickness of $80\mu\text{m}$ and 16 turns per layer. A magnet with a diameter of 10 mm and a height of 20 mm was placed in the middle of the coil with 1 mm gap in between them. This configuration radiates shear waves with linear polarisation from the middle of the coil. This EMAT was placed on top of 40 mm-thick steel specimen opposite to a shear-wave piezoelectric transducer (Panametrics-V151); both piezoelectric transducer and EMAT polarisation directions were aligned to maximise the signal amplitude. A switching board was connected to the coil terminals to control the active number of layers (Fig. 7-a).

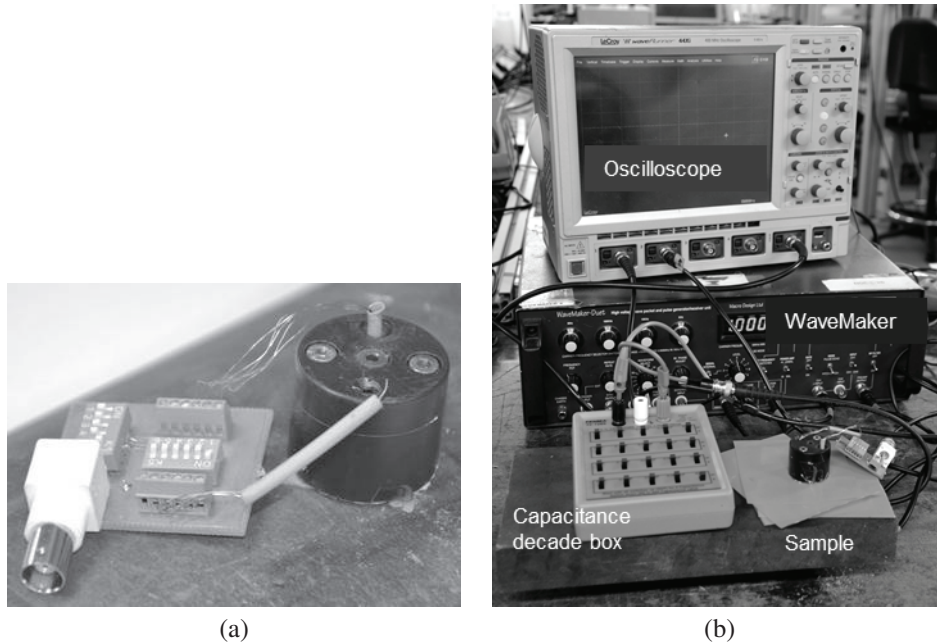


FIGURE 7. EMAT with switching board to selectively add layers to the measurement coil (a) and measurement set-up (b).

The EMAT was connected in series with a capacitance decade box (Tenma-72-7265) to the driver output of the a WaveMaker-Duet system (Fig. 7-b). The capacitance box was used to select the capacitance value that maximises the signal for a given number of layers in the coil; the capacitance was varied from 0.2 to 7 nF in 0.1 nF steps. The piezoelectric transducer was connected to the pre-amplifier of the WaveMaker-Duet system with a 40 dB gain and its

output to the oscilloscope (LeCroy WaveRunner 44Xi, Teledyne LeCroy, New York, US). The driver trigger output of the WaveMaker-Duet system was also connected to the oscilloscope.

The driver of the system was set to generate an 8-cycle tone-burst with a Hann-window tapering and a maximum amplitude of 40 Vpp at 1 and 2 MHz. The driver output was split and connected to the oscilloscope through a high impedance buffer in order to keep a reading of the driver output and confirm there was not distortion in the signal due to saturation. Received signals were synchronised for each measurement using the driver trigger output and averaged 20 times in the oscilloscope to increase the SNR. The maximum voltage recorded was in the range of hundreds of millivolts; results were normalised to the maximum measured value as only relative comparisons of the experimental data were conducted.

First, the frequency was set to 1 MHz and the EMAT lift-off changed to 0, 1 and 2 mm using calibrated non-conductive polymer sheets. Results are shown in Fig. 8 with the curves being normalised with respect to their maximum value; Table 1 gives the relative amplitude of the curves for a 4-layer coil. The capacitance values that maximised the signal are given in Table 2. The amplitude decrease should be attributed, not only to the coil lift-off, but also to the magnet lift-off from the specimen which reduces the bias magnetic field.

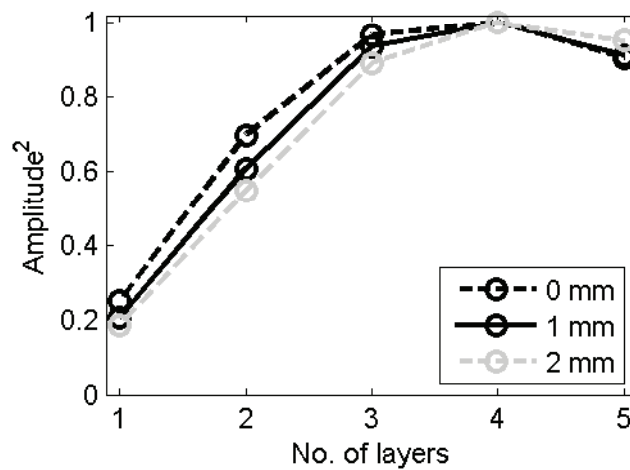


FIGURE 8. Square of the amplitude of the ultrasonic signal received at the piezoelectric transducer vs. number of coil layers in the EMAT. 0, 1 and 2 mm lift-off at 1 MHz. The amplitude of each curve is normalised with respect to its maximum.

TABLE 1. Relative amplitude of the signals for a 4-layer coil at 1 MHz.

Lift-off (mm)	0	1	2
Relative amplitude (squared)	1	0.65	0.28

TABLE 2. Capacitance values (5% tolerance).

Freq.	Lift-off	1 layer	2	3	4	5
1 MHz	2 mm	4 nF	2.2 nF	1.2 nF	.6 nF	.4 nF
1 MHz	1 mm	5 nF	3 nF	1.4 nF	7 nF	.4 nF
1 MHz	0 mm	4 nF	3 nF	1.6 nF	.9 nF	.6 nF
2 MHz	0 mm	2 nF	.7 nF	.4 nF	.2 nF	< .2 nF

The curves in Fig. 8 suggests that the optimal coil inductance is reached with 4 layers – this is when the maximum power transfer condition should be satisfied. An interesting observation is that there is a small difference between the curves and that in all of the cases the signal is maximised with 4 layers at 1 MHz, see Fig. 8. This means that a) changes in the value of the coupling factor k are small and cannot be observed due to the coarse change in the inductance when

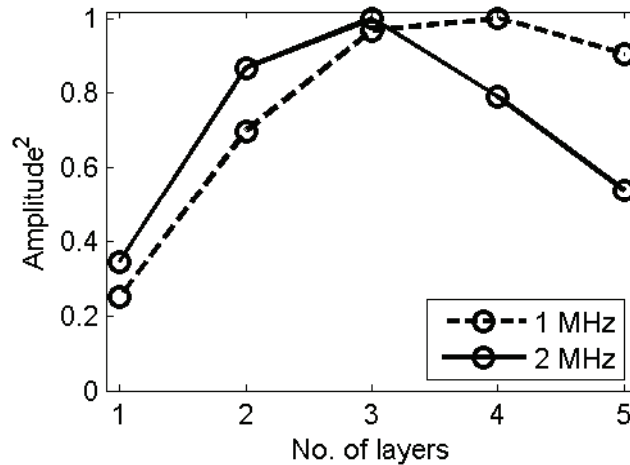


FIGURE 9. Square of the amplitude of the ultrasonic signal received at the piezoelectric transducer vs. number of coil layers in the EMAT. a) 1 and 2 MHz with 0 mm lift-off. The amplitude of each curve is normalised with respect to its maximum. b)

switching between layers, and/or b) the inductance of the coil increases with the distance from the ferromagnetic specimen. The later could be, for example, due to magnetic saturation in the sample caused by the bias magnetic field of the EMAT magnet – when a ferromagnetic material is saturated its permeability decreases [19, 20], and as the bias magnetic field weakens (because the magnet moves away from the specimen) the permeability increases which could also increase the inductance of the coil. Another possibility is that the path of the eddy current and hence its inductance and resistance are modified.

A further observation is that there is a small difference between the capacitance values when the lift-off changes (Table 2). Overall, for this particular design, once the optimal number of turns and capacitance have been set for this frequency, the coil-driver will operate close to the maximum power transfer condition regardless of the lift-off at least within this range. The same results were found for different ferromagnetic mild steel samples.

The experiments were repeated at 2 MHz with no lift-off. Results are plotted in Fig. 9; capacitance values are also given in Table 2. As the frequency increases less layers are required to get the maximum power transfer condition; 3 layers in this case compared to 4 for 1 MHz.

It is important to highlight that at lower frequencies, for example a few kilohertz, many turns should be required to achieved the maximum power transfer condition and this may not be physically possible for certain coil geometries.

CONCLUSIONS

A model has been presented to investigate the optimal impedance of the coil of an EMAT based on the Lorentz force on transmission for 1 and 2 MHz. It was discussed how the number of turns in the coil can be changed to balance the load between the coil (and driver) resistance and the eddy currents such that maximum power can be delivered to the eddy currents. As a result, an external matching network may be unnecessary in most cases. This is important because by solely using an external matching network, which seems to be the standard practice, there may be lack of control on the distribution of the power between the coil resistance and the eddy currents. Additionally the matching network requires more elements, introduces losses and parasitic capacitances which overcomplicates the design and deteriorates its performance.

A convenient series resonant circuit is formed when a capacitor is connected in series with an EMAT coil and a purely resistive driving source. Hence, the current through the coil is maximised at the resonant frequency. Resonance was found to increase the signal strength by roughly 2 dB in the example investigated.

Another observation is that under maximum power transfer condition, the resistance of the source and coil should be the smallest possible to maximise the eddy currents. Which implies that when only a section of the coil is used in the ultrasonic aperture, once the optimum coupling has been achieved the return path should be as short as possible.

Moreover if the frequency increases, less turns in the coil are required to satisfy the maximum power transfer condition. On the other hand, at lower frequencies, for example a few tens of kilohertz, maximum power transfer may not be satisfied for certain coil geometries.

A tunable coil was proposed to change its inductance without affecting the radiation pattern of the EMAT. When using this coil, it was found that the number of turns that satisfy the maximum power transfer condition is almost invariant with the coil lift-off in the range from 0 to 2 mm over mild steel specimens for this particular case.

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