CHARACTERISTICS OF ELECTROMAGNETIC PULSE PROPAGATION IN METAL

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INTRODUCTION

It is well known that the solution of the diffusion equation for an electromagnetic field with a time harmonic term, $e^{i\omega t}$, is in the form of a traveling wave whose amplitude attenuates over distance into a conducting medium. As the attenuation is an increasing function of frequency, the high frequency components attenuate more rapidly than those of low ones upon entering a well conducting object. At the same time, the phase velocity of an individual component is also an increasing function of frequency causing a broadening of the pulse traveling inside a conductor. In the results of our previous study of numerical simulations [1], the problem of using a gaussian input pulse was immediately clear. First, having the dominant frequency components distributed around zero, the movement of the peak was not well defined. Second, with the amplitude of fourier components varying slowly over a wide range, the dispersion–induced blurring of the peak position was seen to be severe.

For the present study, we have used a gaussian modulated single frequency sinusoidal wave, i. e., the carrier, as an input pulse in an effort to improve the issues related to the unclear movement of peak and dispersion as described above. This was based on the following two anticipated advantages: First, the packet moves in a conductor at the group velocity calculated at the carrier frequency [2], which means it is well controllable. Second, the amplitude of frequency components other than that of the carrier can be almost negligible, such that the effect of dispersion can be significantly reduced. A series of experiments of transmitting electromagnetic pulses through aluminum plates of various thickness was performed to test the validity of the above points. The results of numerical simulation based on wave propagation are discussed with respect to the experimental results. Finally, a simple simulation was performed based on diffusion of a continuous sine wave input and the results are compared with those of a single frequency sinusoidal wave observed over time at difference locations inside a conductor.

NUMERICAL SIMULATION BASED ON WAVE PROPAGATION

The input pulse used was a gaussian modulated cosine wave of the following expression:

$$\psi(z=0,t) = \psi_o e^{-t^2/L^2} \cos\omega_o t \qquad (1)$$

The general solution can be constructed by performing the following integral:

$$\psi(z,t) = \int_{-\infty}^{\infty} A(\omega) e^{i(\omega t - z/\delta)} e^{-z/\delta} d\omega$$

where $A(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \psi(z,0) e^{-i\omega t} dt$ is the weighting factor of individual frequency components, $\frac{1}{\delta} = \left[\frac{\omega\mu\sigma}{2}\right]^{1/2}$, σ is the electrical conductivity and μ is the magnetic permeability. The full expression is then obtained to be

$$\psi(z,t) = \frac{L}{2} \int_{-\infty}^{\infty} e^{-z/\delta} [e^{-L^2(\omega-\omega_o)/2} - e^{-L^2(\omega+\omega_o)/2}] \cdot \cos(\omega t - z/\delta) d\omega \qquad (2).$$

Using $\sigma = 1.73 \times 10^7$ Siemens/meter for aluminum 2024 alloy and $\mu = 4\pi \times 10^{-7}$ Weber/Amp-meter, the solution $\psi(z,t)$ was obtained by numerical integration. The complete solution can be represented as a field distribution over time at given locations or that over distance at given times.

Fig. 1 shows the field distribution over time at z = 0 for the gaussian wave packets with carrier frequencies of 0.5 and 1 kHz. The distribution for two different frequencies at z = 5 mm is shown in Fig. 2. The phase velocity of a single frequency component is proportional to $\left(2\omega/\sigma\mu\right)^{1/2}$. Hence, the delay time for detecting the peak at a given location inside the conductor, which in this case is aluminum 2024 filling one half of the infinite space, should be proportional to $\sqrt{\omega^{-1}}$. Details related to wave propagation in metallic conductor can be found in Ref. 3.

In Fig. 2 it is shown that the main peak of a 1 kHz packet appears at z = 10 mm earlier than the peak of 0.5 kHz does. It is also seen that there is no noticeable dispersion

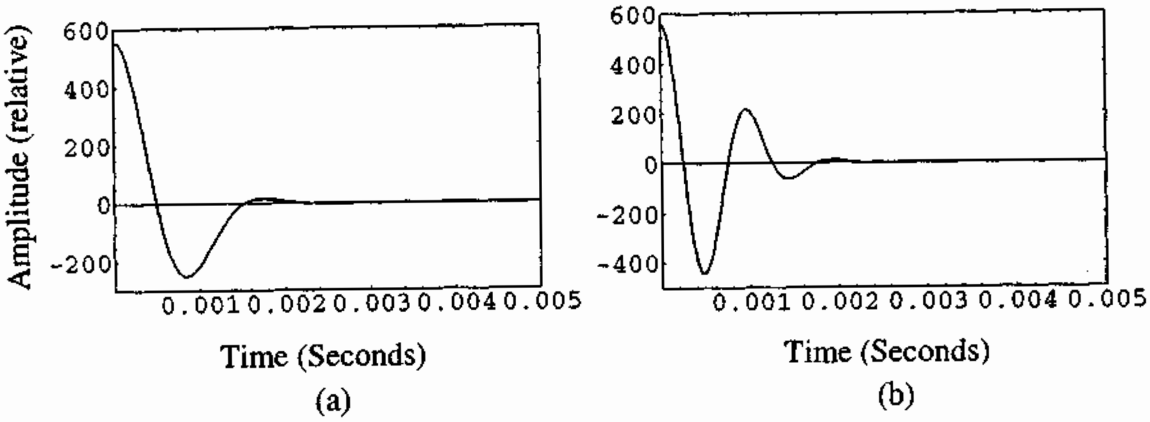


Fig. 1. The field amplitude distribution over time at z = 0 for tone burst signals of 0.5 kHz (a) and 1 kHz (b).

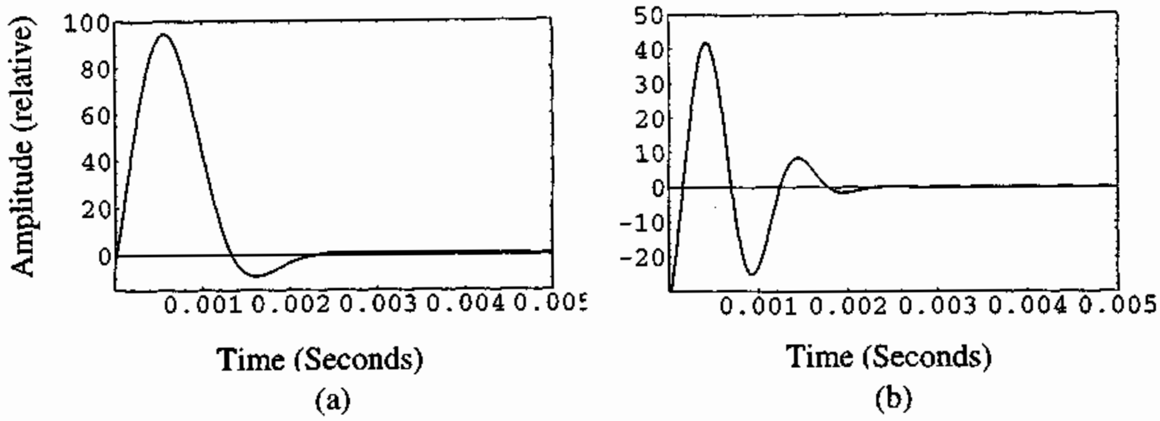


Fig. 2. The field amplitude distribution over time at z = 10 mm for tone burst signals of 0.5 kHz (a) and 1 kHz (b).

of the packet after advancing 10 mm in aluminum. Such findings from the results of the simulation are consistent with the original expectation.

EXPERIMENT AND RESULTS

A simple experiment was performed to test the validity of the solution obtained by integrating equation (2). The experimental setup consisted of a drive coil and a giant magnetoresistance (GMR) sensor. The advantage of using a GMR sensor is that it measures the field amplitude rather than the time rate of change in field amplitude. Therefore, the use of a GMR sensor enables measurements at very low frequency such as 0.5 kHz or even lower. A function generator providing tone burst signals was used to activate the drive coil. A set of aluminum plates with a cross-sectional area of 30 x 30 cm^2 were used to simulate the varying thickness of conducting plate. The signals were sensed at the opposite side of the plates with respect to the drive coil. Fig. 3 shows two waveforms; one taken without a sample and the other taken with a 0.813 mm thick aluminum sample placed between the drive coil and the GMR sensor. The time delay due to the presence of the metallic specimen was measured as the difference between the locations of the first zero crossings observed with and without the specimen.

Fig. 4 (a) shows the time delay as a function of composite thickness of aluminum plates for two difference carrier frequencies of tone burst signals, i. e., 0.5 and 1 kHz. It is interesting to note that all the aluminum plates used, except one, were coated with an Alcad layer which has a conductivity that is considerably higher than that of typical aluminum alloys. Whenever the uncoated aluminum plate was used to form a desired thickness, the delay time dropped as seen at 3.58 and 4.83 mm. Fig. 4 (b) shows the frequency dependence of time delay through 1.016 and 2.032 mm thick aluminum plates.

DISCUSSION

According to the phase velocity of a single component given in the previous section, if the field propagates as a traveling wave, the delay time of a 0.5 kHz tone burst should be longer than that of a 1 kHz tone burst by a factor of $\sqrt{2}$ at any plate thickness. The results of Fig. 4 (a) do not provide strong evidence for this. Also, the results in Fig. 4 (b) do not show the frequency dependence of $f^{-1/2}$ as expected from the phase velocity of a traveling tone burst. Hence, one can say that the results follow the overall trend which is consistent with the prediction based on wave propagation but the agreement is insufficient to clearly support the validity. Of course, the presence of the Alclad coating will add more complication to this. Nevertheless, as will be shown later, the exact functional form is not a significant issue.

Assuming that the field variation is based on wave propagation, one can calculate the characteristic impedance in aluminum as

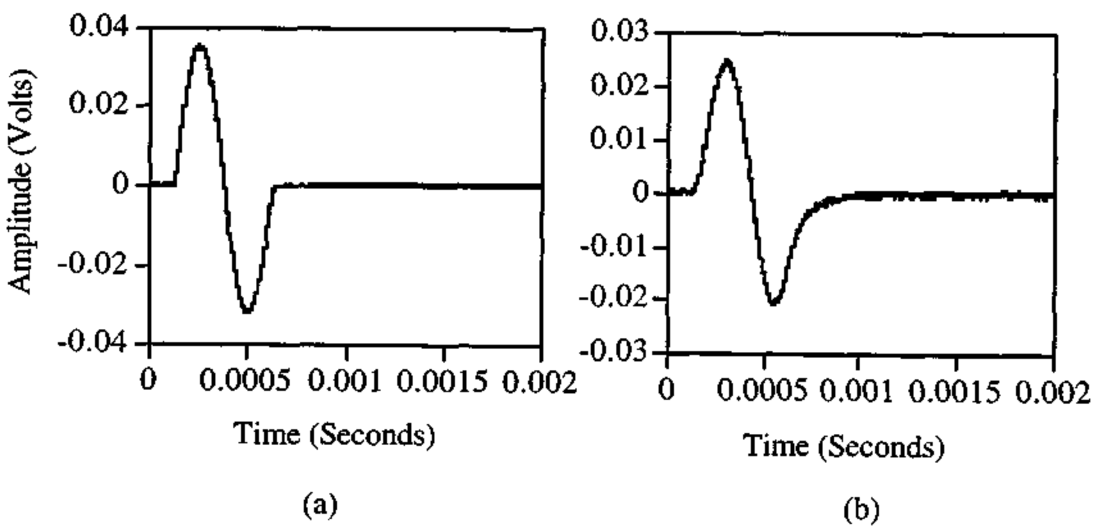


Fig. 3. Magnetic field distribution over time as detected by a GMR sensor with (a) only an air gap and (b) 0.812 mm thick aluminum sample placed between the drive coil and sensor.

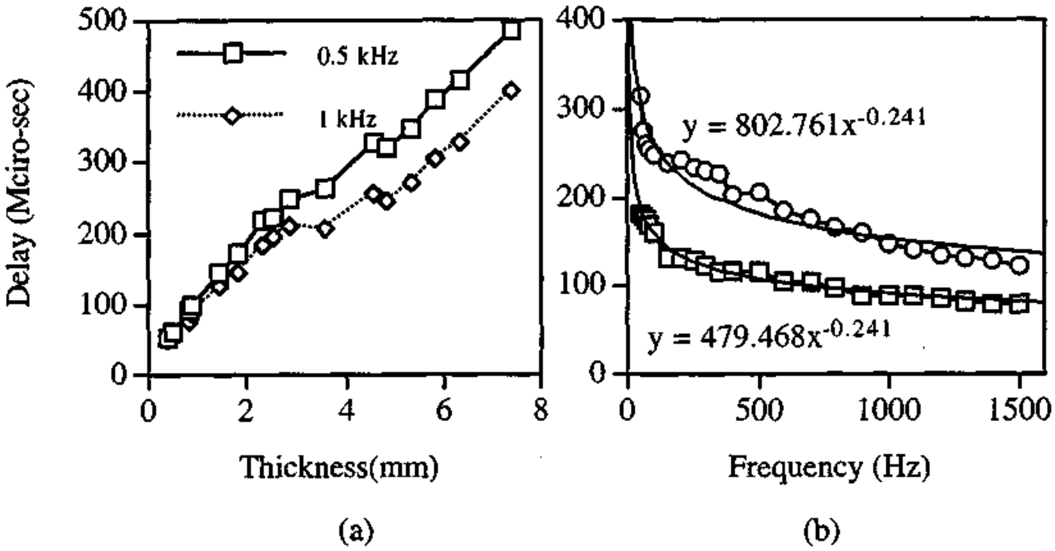


Fig. 4. (a). The delay time as a function of aluminum plate thickness for two carrier frequencies and (b). the delay time as a function of frequency for two different aluminum plate thickness for two plate thickness; 1.02 mm (circle) and 2.04 mm (square).

$$|Z| = \left|\frac{E}{H}\right| = \left|\frac{\omega\mu}{\sigma}\right|^{1/2} = \left(\frac{2\pi \times 10^3 \times 4\pi \times 10^{-7}}{1.73 \times 10^7}\right)^{1/2} = 2.14 \times 10^{-5}\Omega$$

at 1 kHz. When compared with the characteristic impedance in vacuum, which is well approximated as to be that in air [3],

$$Z = \left(\frac{\mu_o}{\varepsilon_o}\right)^{1/2} = 377\Omega,$$

it is clear that there exists an enormous impedance mismatch at the air/aluminum interface. Such a vast difference in the characteristic impedance will certainly cause almost complete reflection of waves at the interface, and, in principle, it should not be possible to transmit even a minute amount of field energy in a metallic conductor. Nevertheless, the experiments proved that the field energy transmits very well and there was no indication of any reflection at interfaces.

As given in the previous section, the wavelength is 3.4 and 2.4 cm at 0.5 and 1 kHz, respectively. These wavelengths are far larger than the thickness of the aluminum plates used in this experiment and the spatial variation of field amplitude within the plate can be neglected, leaving only the time dependent phase factor, $e^{i\omega t}$, effective. Under such condition, the traveling wave characteristics are lost and the complete absence of reflection at the interfaces is explainable, and the experiment does not invalidate the nature of wave propagation. Such an unclearness provided a reason to investigate the properties of diffusing fields, the details of which are given in the following section.

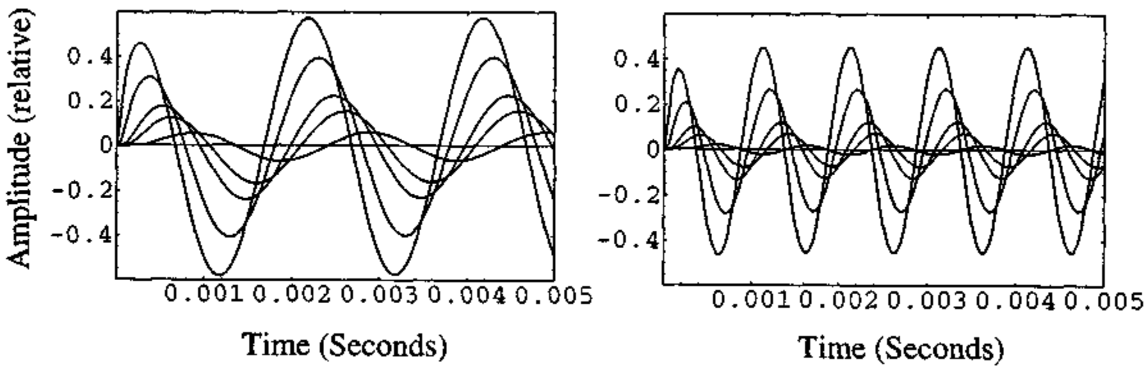
NUMERICAL SIMULATION BASED ON DIFFUSION

As the experimental results of the previous section neither prove nor disprove the validity of the wave characteristics of electromagnetic tone bursts penetrating aluminum plates, it is appropriate to investigate the characteristics of diffusing fields. A numerical simulation was, hence, performed and the details are given in this section. The appropriate mathematical expression for this is found in Ref. 4 as follows:

$$\psi(z,t) = \int_0^t \frac{z}{\sqrt{4\pi a^2 (t-\tau)^3}} e^{-\frac{z^2}{4a^2(t-\tau)}} v(\tau) d\tau \qquad (3)$$

where $a = 1/\sqrt{\sigma\mu}$. The external disturbance occurs over time τ and the upper limit of the integral is to ensure that only the disturbance which has occurred up to a given time t influences the event observed at that time.

For the sake of simplicity and clarity in comparing the results based on the wave propagation and diffusion mechanism, the disturbance, $v(t)$, is chosen to be a continuous function of time, i. e., $\sin\omega_o t$. The results for 0.5 and 1 kHz are presented in Fig. 5 as the field distribution over time at various locations inside an aluminum alloy 2024 filling one half infinite space. It can be clearly seen in both cases that it takes finite time for the field distribution to reach the steady state at a given location inside the metal. It is also interesting to notice that the field amplitude seen at a location is lower at 1 kHz compared to 0.5 kHz showing that a slowly varying field penetrates deeper into a conducting medium. This is exactly the same phenomenon as the temperature change under the



(a) (b)

Fig. 5. Amplitude distribution of oscillating diffusing field over time observed at various locations (z = 3, 5, 8,10 and 15 mm in aluminum) for (a) 0.5 kHz and (b) 1 kHz. The field amplitude decreases sequentially from that observed at z = 3 mm to that observed at z = 15 mm.

earth's surface which reflects the seasonal variation rather than the daily fluctuation. In addition, the field amplitude apparently is a decreasing function of distance into the metal. Nevertheless, such a frequency and travel distance dependence of field amplitude is similar to what is expected from traveling wave propagating into a conductor. Fig. 6 shows the field distribution of single frequency waves of 0.5 and 1 kHz over time at the same locations of Fig. 5.

Clearly, with the only exception of the diffusing field at the initial stage, these two results are identical. On one hand, one may feel that it is remarkable to obtain such identical results using two different approaches. On the other hand, one can see that it is not surprising at all to obtain the same time and spatial dependence of the field inside a conductor for the two approaches since they are merely based on different interpretation of a single equation.

CONCLUSION

The present study proves experimentally that it is possible to transmit electromagnetic tone burst of 0.5 and 1 kHz through a bulk aluminum plate several millimeters thick. The arrival time and shape of the tone burst signal transmitted through aluminum plates are seen to be consistent with what is predicted from the damped traveling wave. It is, however, clear that there exist no useful traveling wave characteristics since the field inside an aluminum plate is almost static in nature and the large impedance mismatch at interface is meaningless. The most notable accomplishment of the present study is the discovery of the identical behavior of damped traveling wave and the oscillating diffused field.

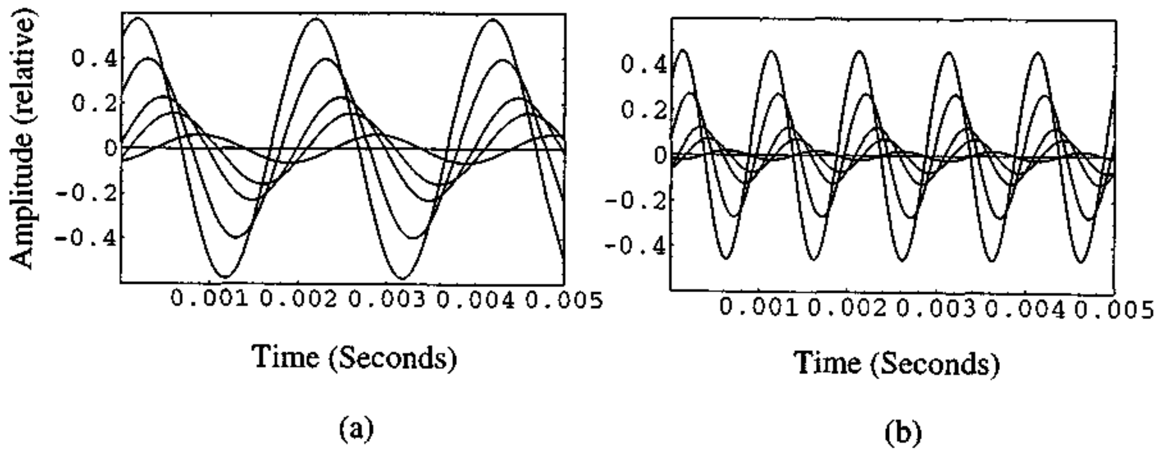


Fig. 6. Amplitude distribution of monochromatic traveling wave over time observed at various locations (z = 3, 5, 8, 10 and 15 mm in aluminum) for (a) 0.5 kHz and (b) 1 kHz. As in Fig. 6, the field amplitude decreases sequentially from that observed at z = 3 mm to that observed at z = 15 mm.

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