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NEW PROPOSAL FOR THE DETECTION OF CONCEALED WEAPONS

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ABSTRACT

A new concealed weapon detection system able to work in open areas without invading individual privacy is presented. This approach is based on pulse induction technology. The paper describes the use of a uniform magnetic field generator for transmitting Heaviside step pulses that cause eddy currents to flow in any metal object carried by the person. The eddy currents excited in the metal body take the form of an exponentially decaying transient immediately following sudden changes in the exciting magnetic field. This decay curve can be used to obtain a time constant which is highly dependent on the size, shape and material composition of the object. A mathematical model of the new concealed weapon detection system is presented showing how the time constant of different metallic objects can be calculated and potentially used as a signature for weapon detection and identification. Simulation results are presented showing the new system is sensitive to the weapon shape but is insensitive to the weapon orientation and the strength of magnetic flux.

Keywords— concealed weapon detection, magnetic field, eddy currents, time constant.

1. INTRODUCTION

Nowadays, terrorist groups, hijackers, and people hiding guns and knifes are a constant and increasing threat. Concealed weapon detection has turned into one of the greatest challenges facing the law enforcement community today in terms of crime prevention and anti-terrorism [1]. Current screening procedures for detecting concealed weapons such as handguns, knives are common in controlled access settings such as airports, entrances to sensitive buildings, and public events. Unfortunately screening in this way, prior to entering controlled areas, is sometimes ineffective in preventing some weapons from getting through and also produces bottle-necks in crowded environments. A reliable concealed weapon detection system able to work in an open area and able to discriminate between ferromagnetic weapons is necessary. In order to discriminate ferromagnetic weapons, a parameter which can be used as a signature for weapon discrimination has to be found.

To begin with, a weapon detection system based on pulse induction technology able to work in open areas without invading individual privacy is being studied. This approach includes the use of a uniform magnetic field generator [2] for transmitting Heavy step pulses that cause eddy currents to flow in any metal object carried by the person. The eddy currents excited in the metal body take the form of an exponentially decaying transient immediately following sudden changes in the exciting magnetic field. This decay curve can be used to obtain a time constant of the current decay which is highly dependent of the size, shape and material composition [3]. A numerical model is presented to study the potential use of time constant as a signature for weapon discrimination and simulation results are presented and discussed.

2. THEORY FOR ELECTROMAGNETIC WEAPONS DETECTION AND IDENTIFICATION

The proposed method uses low frequency electromagnetic fields and is based on suitable solutions of Maxwell’s equations. The difficulty comes when computing the magnetic field scattered from conductive masses when it is energised with a low frequency electromagnetic field. The subject has been analysed in detail by Kaufman and Keller [4].

To solve the problem, the weapon is approximated to a sphere with radius “a” and a conductivity “σ” and is irradiated with an electromagnetic wave in the form of step pulses. When the pulse occurs, the weapon is illuminated by a step change in the amplitude of the magnetic field vector which is considered to be planar in the vicinity of the weapon. The magnetic field in the vicinity of the weapon is defined as “H_0”.

Using a quasi-static solution of Maxwell's equations, it is found that the primary magnetic field around the sphere is increased by an amount due to currents to flow within the sphere given by the following three equations (for more details see [4])

$$E_\phi^a = \frac{3KB_0 a^3 \sin\theta}{R^2} \sum_{s=1}^{\infty} \frac{q_s e^{-q_s t}}{[k_s{}^2 a^2 + (K-1)(K-2)]} \tag{1}$$

$$B_R^a = \frac{6KB_0 a^3 \cos\theta}{R^3} \sum_{s=1}^{\infty} \frac{e^{-q_s t}}{[k_s{}^2 a^2 + (K-1)(K-2)]} \tag{2}$$

$$B_\theta^a = \frac{3KB_0 a^3 \sin\theta}{R^3} \sum_{s=1}^{\infty} \frac{e^{-q_s t}}{[k_s{}^2 a^2 + (K-1)(K-2)]} \tag{3}$$

where "E_ϕ^a", "B_R^a", "B_θ^a" are the only components of the anomalous fields caused by currents induced in the sphere. These components are expressed in a spherical coordinate system centred on the sphere, with "R" being in the direction of the incident field. The others quantities in the equations as defined as:

$K = \mu / \mu_0$ (The relative magnetic permeability of the weapon) (4)

$q_s = k_s^2 / \sigma\mu$ (5)

$k_s = \pi s / \alpha$ ($s=1, 2, 3,\ldots,\infty$) (6)

and "t" is time, following the initiation of the current step.

The form of each electromagnetic field component is that of a sum of exponentially decaying transients. The asymptotic behaviour of these transients is now examined. During the early part of the transient response of the electromagnetic field (t→0), the expressions for the anomalous magnetic field components are as follow:

$$B_R^a = B_0(a/R)^3 \cos\theta[1 - 6/\sqrt{\pi}(\alpha t)^{1/2}] \tag{7}$$

$$B_\theta^a = B_0 1/2(a/R)^3 \sin\theta[1 - 6/\sqrt{\pi}(\alpha t)^{1/2}] \tag{8}$$

During the late part f the transient decay, the field is almost entirely determined by the first exponential terms:

$$B_R^a = \frac{6B_0}{\pi^2}\left(\frac{a}{R}\right)^3 \cos\theta e^{-\frac{t}{\tau_0}} \tag{9}$$

$$B_\theta^a = \frac{3B_0}{\pi^2}\left(\frac{a}{R}\right)^3 \sin\theta e^{-\frac{t}{\tau_0}} \tag{10}$$

$$E_\phi^a = \frac{3B_0 a}{\tau_0 \pi^2}\left(\frac{a}{R}\right)^3 \sin\theta e^{-\frac{t}{\tau_0}}, \text{ where } \tau_0 = \sigma\mu\alpha^2\pi^2 a \text{ is a time constant.} \tag{11}$$

These results are the basis for the design of a highly effective weapons detection system. Each of the three expressions for field components is of the form of a product of two terms, the first term of which involves only the geometry and magnitude of the primary field in the vicinity of the weapon, and a second term involving a time constant, but independent of the geometry and strength of the field incident on the weapon. Measurement of the time constant provides a means for weapon detection which is free of false alarms due to variations in primary field strength.

A time constant can be determined from a plot of the transient magnetic field on semi log graph paper (the slope of the curve is the time constant). The time constant can also be determined from the expression:

$$\tau_0 = -\frac{B_R^a}{\partial B_R^a / \partial t} = -\frac{B_\theta^a}{\partial B_\theta^a / \partial t} \tag{12}$$

The time constant is a function only of the conductivity-permeability product of a sphere and its cross sectional area.

Weapons have a complex geometry, so a question arises as to whether or not conclusions for simple geometries extend to more complicated shapes. Kaufman and Keller (1985) extended the analysis to axial symmetry and arrive at an expression for the scattering time constant as follows:

$\tau_0 = \sigma\mu\alpha^2 / q$, where "q" depends on the shape of the conductive body. (13)

The expression shows the potential of the time constant in identifying a specific weapon of an even more complicated shape. All weapons of the same size, shape and metallic composition will be characterised by a scattered electromagnetic field from an incident current step will be the same, no matter what the strength or the incident field on the distance of the weapon from the transmitter or the receiver array. Thus weapons can be classified at least within the precision with which the time constant of the decaying magnetic field can be determined.

3. TIME CONSTANT OF A TYPICAL WEAPON

The appropriate way to determine the time constant for a real weapon is by illuminating that weapon with an electromagnetic field using step pulses and measuring the time constant from the decaying field. Usually the weapon will be carried on the body of a person. However the time constant associated with the human body might obscure that of the weapon. An estimate as to whether this will happen can be made by substituting numbers in the expression (13). For example, assume that the conductivity-permeability of the steel in a weapon is of the order of 1 siemens x henries x square meter, the radius of the sphere enclosing a weapon is 0.1 meter, the form factor "q" is 10 (the more convoluted the shape of the metallic object the greater will be the form factor). With these numbers, the order of magnitude estimate for the time constant of the hypothetical weapon is 1 millisecond. In the human body, flesh and bone are conductive and the conductivity-permeability product for a human body is of the order of 10 siemens x henries x square meter. Thus the corresponding order of magnitude time constant for a human body is 0.1 microsecond. Although these are only estimates, the two time constants are so different that there is no likelihood that one will obscure the other.

4. PROPOSED WEAPON DETECTION SYSTEM

A non-obtrusive weapon detection system based on pulse induction technology able to work in open areas without invading individual privacy is being studied. The current approach includes the use of magnetic field generator for transmitting electromagnetic step pulses that cause eddy currents to flow in any metal object carried by the person. The proposed magnetic field generator consists of a group of parallel current carrying cables laid below the floor that produce a horizontal magnetic field. This field falls off more slowly at the edges than that produced by conventional loop coils. The eddy currents produced in the metal object generate a magnetic signal that is detected by arrays of magnetic field sensors as illustrated in Figure 1.

The eddy currents excited in the metal body take the form of an exponentially decaying transient immediately following sudden changes in the exciting magnetic field. This decay curve can be used to obtain a time constant of the current decay. The transient time decay is a sum of exponentials, where the late part of transient decay is entirely determined by the first exponential term.

Algorithms for an accurate determination of a time constant must be developed. The present stage of the project is focalised in experimental tests leaving for later stage signal processing and developing of algorithms for time constant extraction. However one of the intended algorithms consists of the transformation of the signal strength by using the logarithm of the signal. With this transformation, an exponential decay curve appears as straight line, with the slope being the time constant. We can see this transformation in plots of figure 4, 6, 7, and 8. The time constant (slope of the line) can be extracted by curve fitting (best-fit one –parameter linear function) of the transformed data.

The authors in [3] found that for a sphere illuminated with an electromagnetic wave in the form of step pulses, the time constant is independent of the strength of the field incident magnetic field and highly dependent of the size, shape and material composition. If a metal body is shown to have a unique time decay response, a library of potential threat metal objects can be developed. When a metal body is encountered in the field, its time decay response can be compared to those in the library, and if a match is found, the metal body can be classified.

To test the method a simplified 3-D model in COMSOL 3.3 (figure 3) has been used. It is suitable to analyse sensitivity/insensitivity of induced current response to changes in shapes and orientation of interrogated objects. The model consists of a magnetic field generator (20 parallel cables laid on the floor, 2cm in between) for transmitting step pulse of current of 10A, 1.5ms width, fall time 170us, causing eddy currents to flow in a nearby metal object (60cm over the cables). The eddy currents scatter a signal that will be detected by a three-axis magnetic sensor array (hall or magneto-resistive sensors) placed between the cables. Parameter values used in the model are based on previews studies and simulations performed to achieve a strong enough magnetic field.

5. SIMULATIONS

5.1 SENSITIVITY TO OUTER SHAPE

Four different samples: Gun1 with smooth barrel and smooth bore, Gun2 with square barrel and smooth bore, and two knives with different cross section as showed in figure 2 are tested independently. In figure 3, the magnetic flux density (B) along z-axis and y-axis is picked up at 35cm from the object along perpendicular line between object and floor. Following the intended algorithm for time constant extraction, logarithm of magnetic flux density is plotted against time in order to show more clearly time constant of each interrogated object (figure 4).

5.2 INSENSITIVITY TO OBJECT ORIENTATION

In the following test a gun (steel) is oriented in three positions as seen in figure 5. Results showed that even the amplitude of the signal changes the time of decay stays invariant. Also the measurements have been taken at different distance from the gun (15cm and 35cm as shown in figure 6) to show how the time constant is independent of the strength of the field incident.

5.3 SENSITIVITY TO SIZE

Three guns of the same type but different sizes are tested. In this test a coil is added to the model to sense the time decay of induced current (Eddy current) caused for the abrupt change of the magnetic field. Results in figure 7 show that time constant is a function of cross sectional area of the sample. Because large metallic objects store more energy than small ones, time decay of collapsing magnetic field (or induced current in the coil) takes longer. This characteristic could be potentially used to discriminate object size.

5.4 SENSITIVITY TO MATERIAL COMPOSITION

A same sample (gun1 as seen in figure 2) with different material composition (copper, iron, and steel) is tested. The time constant profile is clearly different for each case confirming the potential of the new weapon detection system to identify objects with different material composition.

6. CONCLUSIONS

Tests have shown that time decay measurements obtained from simulations of the proposed weapon detection system are sensitive to the shape, size, and material composition of the target. Furthermore, the time decay profile is independent of the strength of the magnetic flux density and is independent of distance from the sample. Measurements taken in any direction also show an agreement in time decay profile and the magnitude of the received signal at 45 cm from the sample is of the order of 10^{-5} Tesla. There are many magnetic sensors on the market able to detect these levels: search-coil magnetometer; flux-gate magnetometer; SQUID magnetometer; GMR etc). The results look very encouraging in terms of effectiveness and reduction in the level of false alarms.

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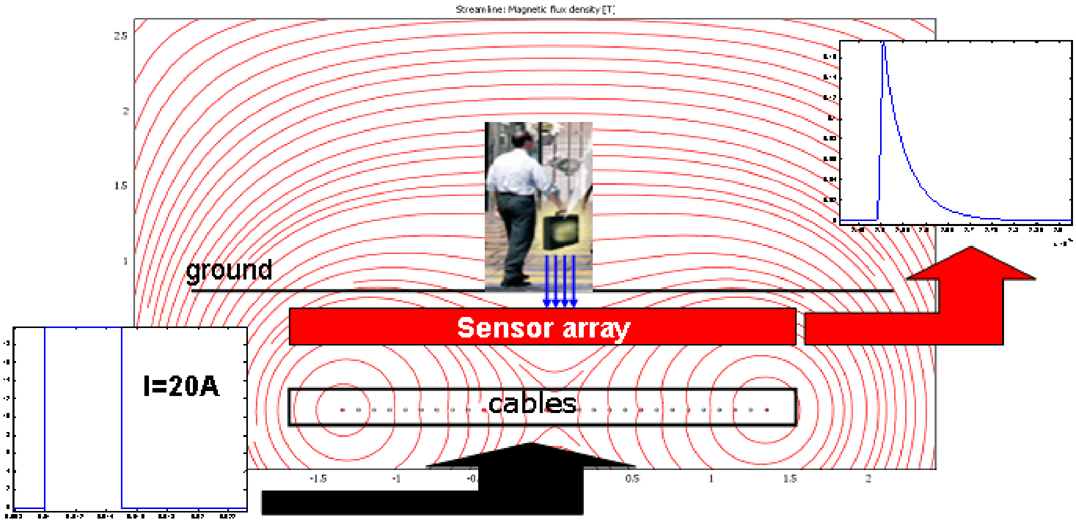
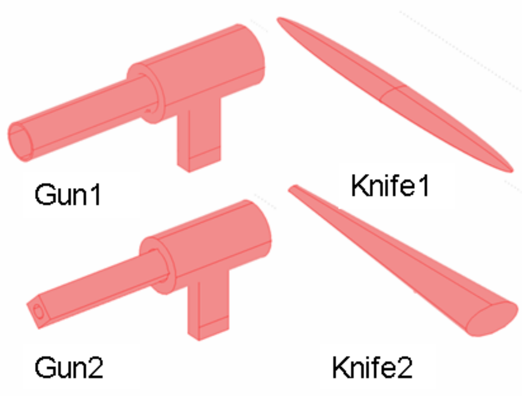


Figure 1. Diagram showing arrange of the magnetic field generator and array of sensors to pick the weapon signals in an open area.



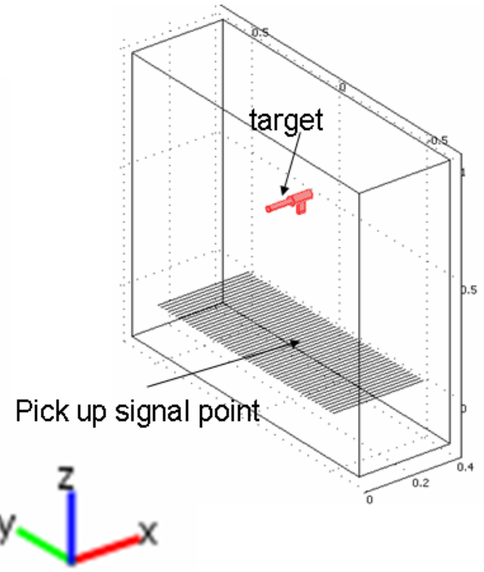


Figure 2. Samples.

Figure 3. 3-D Model

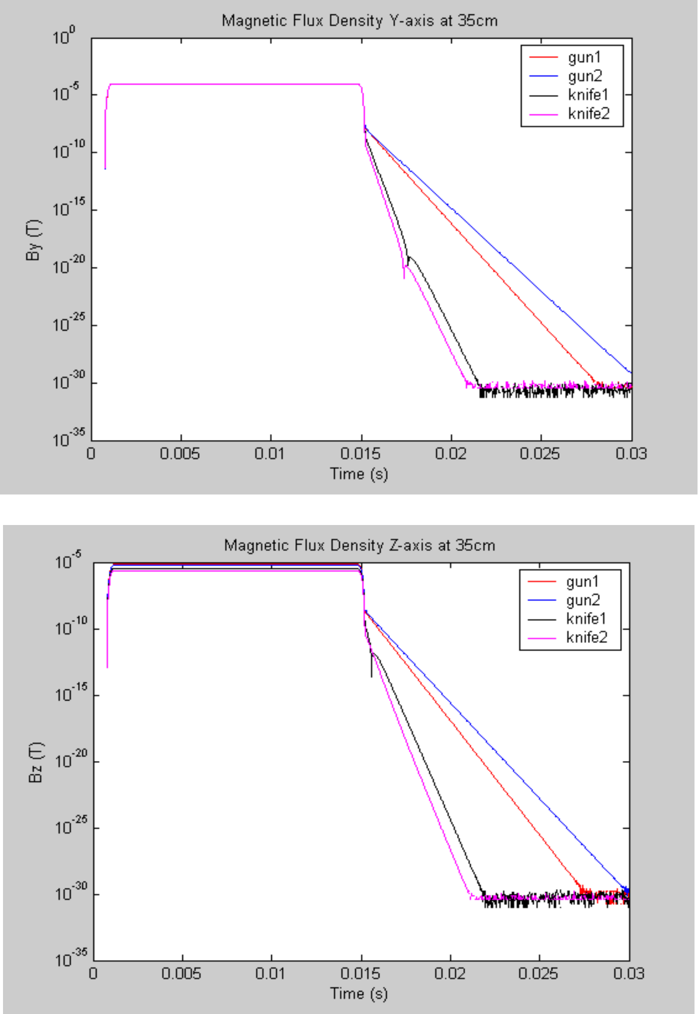


Figure 4. (Top) Time constant profile from measurements of B along y-axis (Bottom) Time constant profile from measurements of B along z-axis

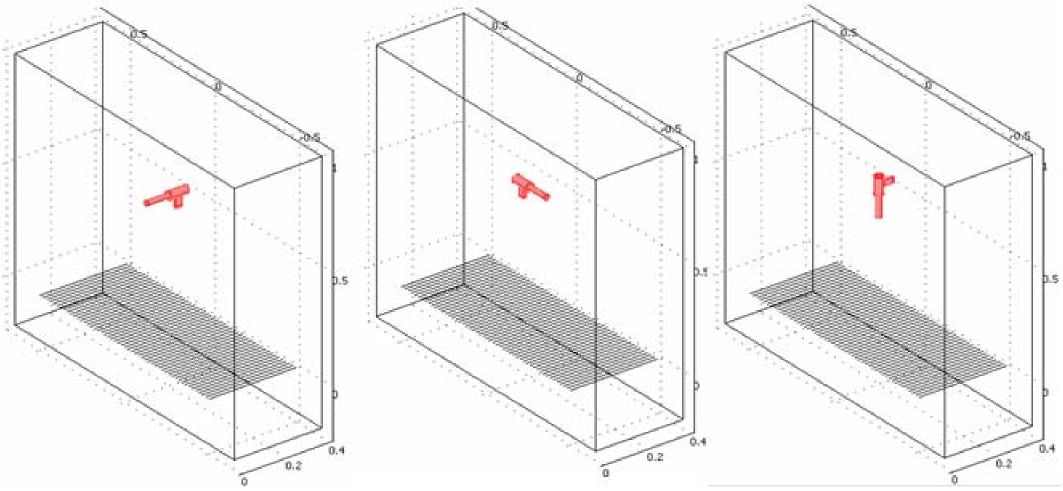
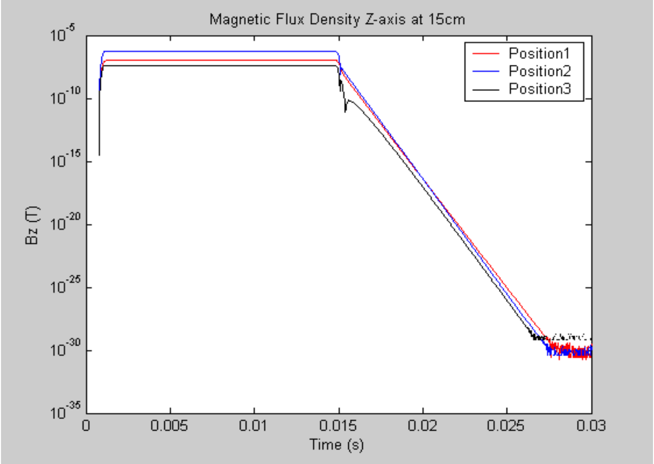


Figure 5. Same object tested at different orientations.



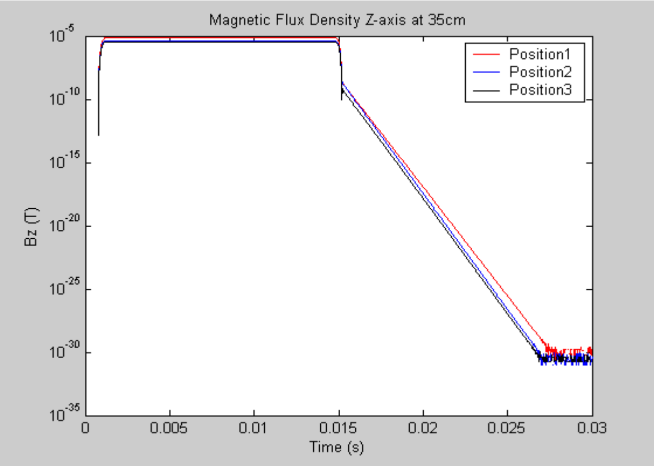


Figure 6. (Top) Time constant profile obtained from measurements taken at 15 cm below the gun. (Bottom) Time constant profile obtained from measurements taken at 35 cm below the gun.

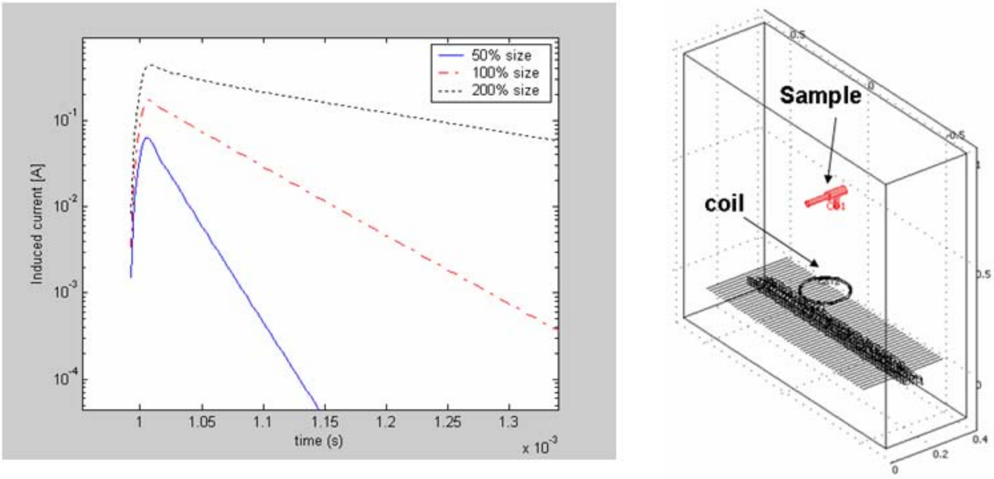


Figure 7. (Left) Time constant profile of the three different size guns. (Right) Model

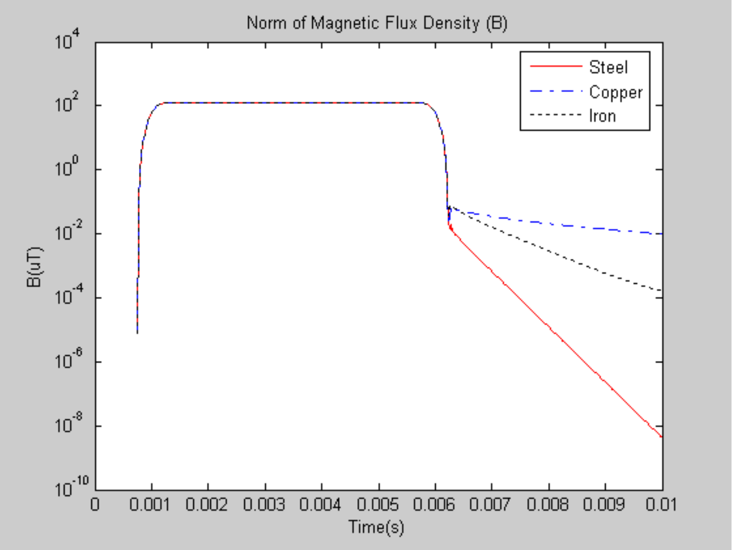


Figure 8. Time constant profile of a gun made of steel, copper and iron