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NOLTR 63-55

RADHAZ PROOF MAGNETIC COUPLING

9 MAY 1963

NOL
UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 63-55

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RADHAZ PROOF MAGNETIC COUPLING

Prepared by:

Edward A. White

ABSTRACT: A transformer can be constructed as a low frequency band pass filter by introducing a highly conductive and low permeability material between the primary and secondary windings of the transformer. Starting with Maxwell's equations, and assuming first a sinusoidal input signal, the output voltage is obtained as a function of frequency, along with an expression for the frequency where the maximum voltage occurs. Then with a step input, the voltage and power output characteristics are given as a function of time. Experimental data is presented confirming the predictions of both cases. At the end of the report two simple systems are proposed as possible communication links between the aircraft and weapon; one being a tuned circuit arrangement and the other a pulsing system. In both cases it is shown that RADAR will not affect the internal components of the weapon as long as the weapon is completely surrounded by a conducting shield.

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NOLTR 63-55 9 May 1963

This report is intended to show the effectiveness of a properly shielded transformer as a low frequency band pass filter, which could easily be adapted as a RADHAZ proof aircraft-weapon communication link. This project was conducted under Weptask No. RMMO-22-006-1.

R. E. ODENING
Captain, USN
Commander

R. E. Grantham
R. E. GRANTHAM
By direction

ILLUSTRATIONS

RADHAZ PROOF MAGNETIC COUPLING

INTRODUCTION

1. The RADHAZ problem for free fall weapons has been attacked from various directions, where a multitude of partial solutions have been proposed. A complete solution to the problem is to completely encase the weapon in a conducting shield so that high frequency signals are not able to penetrate the skin. Now the problem arises as to how does one communicate with the weapon. The following report deals with a method of communication by propagating low frequency electromagnetic radiation through a conducting medium. The discussion is restricted to one dimensional magnetic field flow perpendicular to the conducting material. Essentially two cases are considered, a sinusoidal input and a step function input. It is shown theoretically and experimentally that energy from a low frequency magnetic field will penetrate the conductor and that energies from signals whose frequencies are above 10 KC will be attenuated to a negligible value, yielding a device which is a low frequency band pass filter.

THEORETICAL STUDY

2. The discussion in this section will be concerned with the transfer of magnetic energy through various media and boundaries. The problem can be briefly pointed out in Figure 1(a). A current i_1 flows in windings N_1, producing a magnetic field H_1, which is propagated through a new medium (x) as H_x and into the secondary core as H_2 and produces the current i_2 in the windings N_2. The evaluation of these parameters and their dependence upon the physics of the machine is best described through an interpretation of Maxwell's equations, i.e.,

$$\nabla \cdot \vec{B} = 0 \tag{1}$$

$$\nabla \cdot \vec{E} = \rho/\epsilon \tag{2}$$

$$\nabla \times \vec{H} = \vec{I} + \epsilon\ (\partial\vec{E}/\partial t) \tag{3}$$

$$\nabla \times \vec{E} = -\ \partial\vec{B}/\partial t \tag{4}$$

where

$\vec{B}$ is the magnetic flux
$\vec{H}$ is the magnetic field
$\vec{I}$ is the true current density
$\vec{E}$ is the electric field intensity
ρ is the charge density
t is the time

The current density $\vec{I} = \overleftrightarrow{\sigma}\vec{E}$ where $\overleftrightarrow{\sigma}$ is the electrical conductivity tensor. If one takes the curl of equation (3) and (4) and assumes that the medium is a good conductor, so that $\nabla \cdot B$ and $\nabla \cdot E = 0$, then a diffusion equation can be written for the quantities H, E and i, i.e.,

$$\nabla^2\vec{H} = \sigma\mu\ (\partial\vec{H}/\partial t) \tag{5}$$

$$\nabla^2\vec{E} = \sigma\mu\ (\partial\vec{E}/\partial t) \tag{6}$$

$$\nabla^2\vec{i} = \sigma\mu\ (\partial\vec{i}/\partial t) \tag{7}$$

where

μ is the magnetic permeability

3. First let us consider the case where the current flowing in windings N_1 and the magnetic field produced by the current are sinusoidal as $e^{j\omega t}$. Equation (5) then becomes

$$\nabla^2 \vec{H} = j\omega\sigma\mu\vec{H} \tag{8}$$

The case in general may be approximated by **Figure** 1(b), where the magnetic field H is directed in the x direction only, producing a current i in the copper media in the z direction only. Equation (7) is written as

$$\frac{\partial^2 i_z}{\partial x^2} = j\omega\sigma\mu i_z = \tau^2 i_z \tag{9}$$

where

$$\tau^2 = j\omega\sigma\mu$$

Hence

$$\tau = (1 + j)\sqrt{\frac{\omega\mu\sigma}{2}} = \frac{1 + j}{\delta} \tag{10}$$

where

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \tag{11}$$

Which is called the skin depth, i.e., that penetration where the induced current and associated magnetic field H_x is reduced to 1/e of its value at the surface x = 0.

4. Equation (8) in our case can be written in the same form as equation (9), i.e.,

$$\frac{\partial^2 H_x}{\partial x^2} = j\mu\omega\sigma H_x \tag{12}$$

When the appropriate boundary conditions are applied the solution of equation (12) is written as

$$H_x = H_o e - (1 + j)\ x/\delta \tag{13}$$

where H_o is H_x when $x = 0$.
Which describes the complex magnetic field in the conductor as is shown in Figure 2.

5. By coupling equation (13) with Faraday's induction law, i.e.,

$$V = \mu\int_0^A \frac{\partial}{\partial t} H.dA \tag{14}$$

The voltage developed in the secondary windings N_2 is then

$$V_2 = j\omega\mu AN_2H_oe^{-(1 + j)\ x/\delta} \tag{15}$$

whose absolute value is

$$|V_2| = \omega\ AN_2\mu H_oe^{-x/\delta} \tag{16}$$

6. Assuming at this point that H_o is constant with frequency than a plot of V_2 versus ω will show a peak at

$$\omega_c = \frac{8}{x^2\mu\ \sigma} \tag{17}$$

as is shown in Figure 3 for various values of x. In practice, however, H_o is not a constant with μ since it is a direct function of i_1. At very low frequencies i_1 is not a severe function of ω, but at frequencies above 100 cycles per second i_1 is definitely affected by ω since

$$i_1 = \frac{V_0}{R_1 + j\,\omega L_{s1}} e^{j\omega t} \tag{18}$$

where the equivalent circuit is shown in Figure 4(a). The resistance R_1 is more than the dc resistance of the windings N_1. The conducting sheet (x) acts as a single turn load to the primary and is essentially resistive, although it is frequency depended. Hence at frequencies above about 100 cycles per second H_o is written as

$$H_o = \frac{N_1}{2\pi r} \times \frac{V_0}{R_1 + j\omega L_{s1}} e^{j\omega t} \tag{19}$$

where r is the radius of the solenoid.

7. The magnitude of V_2 in this case is then

$$|V_2| = K_1 \frac{\omega e^{-x/\delta}}{\sqrt{\omega^2 L_{s1}^2 + R_1^2}} \tag{20}$$

where

$$K_1 = \frac{N_1 N_2 \mu_{Fe} A V_0}{2\pi r}$$

μ_{Fe} representing the permeability of iron. The maximum frequency here is given by

$$\omega_c = \frac{8}{x^2 \mu\sigma} - f(L,R) \tag{21}$$

where f(L,R) varies with the core geometry turns ratio and the material and thickness of the conducting material.

8. To investigate energy transfer from a step input function we begin again with Figure 4. When switch S is close the current flowing in windings N_1, is

$$i_1 = i_o \left(1 - e^{-(R_1/L_{s1})t}\right) \tag{22}$$

where $i_o = V_o/R_1$, and the associated magnetic field produced is

$$H_1 = H_o\left(1 - e^{-(R_1/L_{s1})t}\right) \tag{23}$$

where

$$H_o = \frac{N_1}{2\pi r}\, i_o = \frac{N_1}{2\pi r}\;\frac{V_o}{R_1}$$

A solution of equation (12) after applying the appropriate boundary condition, is in this case

$$H_x = H_o e^{-x/\delta_s}\left(1 - e^{-(R_1/L_{s1})t}\right) \tag{24}$$

where δ_s is

$$\delta_s = \left[\frac{1 - e^{-(R_1/L_{s1})\,t}}{\sigma\mu\,(R_1/L_{s1})\,e^{-(R_1/L_{s1})\,t}}\right]^{1/2} \tag{25}$$

The skin depth (δ_s) from a step input is therefore dependent on time as well as the electrical conductivity σ, the permeability μ and the circuit parameters R_1 and L_{s1}. The voltage V_2 developed across N_2 is then

$$V_2(t) = N_2\mu \frac{\partial}{\partial t} \int_0^A H_x \cdot dA \tag{26}$$

$$= \frac{N_1 N_2 A\mu_{Fe}}{2\Pi r} \frac{V_o}{L_{s1}} e^{-x/\delta_s} \left(e^{-(R_1/L_{s1})t} + \frac{x}{2\delta_s}\right)$$

9. The energy (W) delivered to the load resistor R_L is given by (c.f. Figure 4(b))

$$W = i_2{}^2(t)\, R_L T \tag{27}$$

where T = the duration of $V_2(t)$ and

$$i_2(t) = \frac{N_1 N_2 A\mu_{Fe}}{2\Pi r} \frac{V_o}{L_{s1}} \frac{e^{-x/b_s}}{R_2 + R_L} \left\{ \frac{x}{2\,{}_s} \right.$$

$$\left(1 - e^{-((R_2 + R_L)/L_{s2})t}\right)$$

$$+ \left(\frac{R_1 L_{s1} L_{s2}}{L_{s1}(R_2 + R_L) = R_1 L_{s2}}\right)$$

$$\left. \left(e^{-(R_1/L_{s1})t} - e^{-((R_2 + R_L/L_{s2})t}\right) \right\} \tag{28}$$

The energy delivered to a load is then dependent on the size, geometry and turns ratio of the transformer and highly dependent on the thickness and physical properties of the conducting shield. The dependence on L_{s1} and L_{s2} is in turn essentially constant with x, as will be shown in the next section.

PARAMETER EFFECTS AND EXPERIMENTAL RESULTS

10. In the preceding section we developed both voltage and current equations, which describe the energy propagation process from one medium to another, when the input signal is sinusoidal and when it is a step function. In this section we hope to confirm these expressions, at least in part, by some experimental results that have been obtained.

11. Let us take the sinusoidal case first where only a limited amount of experimental work was performed. In this case voltage measurements were made across a secondary load of 0.75 ohms as a function of the driving frequency $\omega/2\pi$. A plot of the output to input voltage ratio versus the driving frequency ($\omega/2\pi$) is given in Figure 5. The physical properties of the device are shown in the figure. Over the frequency range of 1 KC to 200 KC the variation of V_{out}/V_{in} ranges from 10^{-1} to 2×10^{-5} indicating a very definite filtering action. The corresponding curves shown in Figure 3 show that the curve should have peaked at about 20 KC, but a closer look at the equation (22) indicates a term dependent upon the resistance and inductance of the circuit which is subtracted from the term $8/x^2\mu\sigma$ which compensates for the variation in the two curves.

12. The bulk of the experimental work was performed where the input was a step function. The information desired was the energy transmitted through the conducting shield to the resistive load connected across the secondary windings. Figure 6 shows plots of the energy delivered to the resistive load R_L as a function of the shielding thickness x and the core area cross section. The physical parameters of the materials are given in the figure. The input voltage in all cases was 28 volts. The energies transferred range from 1000 to 800,000 ergs, which are adequate for firing electro-explosive devices. The theoretical curves and experimental data

(points) on the curve fit very well. The values of the leakage inductance looking from the secondary L_{s2} was constant with the turns ratio N_2/N_1 and both the primary and secondary leakage inductances L_{s1} and L_{s2} were constant with the shielding thickness x.

13. All the discussions of this report have been restricted to electrical energy transfer. It is also possible to transmit electrical energy by doing mechanical work, such as separating two sections of a magnetic core. This type of investigation has been conducted at the Naval Ordnance Laboratory by Mr. Roland Schlie.

14. Figures 7 and 8 are possible communication systems, using the aforementioned principles as the communication link. Figure 7 shows a system which uses a sinusoidal input to drive different tuned circuits. Each tuned circuit operating at a different frequency would be a selection for the pilot. Prior to separation or bomb release the core is energized with a dc current, and as the bomb is released a signal on the secondary windings arms the weapon. Figure 8 shows a system which incorporates a series of step input voltages to select the arming and fuzing sequences desired. The second transformer is energized prior to separation and the pulse generated at separation arms the weapon. Both systems would have to be armed deliberately by the pilot so that an accidental release or a desired jettison would leave the weapon in a safe condition.

CONCLUSIONS

15. A transformer whose primary and secondary windings are wound on iron cores will exhibit the behavior of a low frequency band pass filter, if the iron cores are separated by a thin conducting sheet. This has been shown theoretically and experimentally. For a copper sheet .040

inches thick the attenuation of the magnetic field at 100 KC is greater than 2 orders of magnitude, and at one megacycle it is attenuated by seven orders of magnitude. The associated electric field is attenuated some 8 orders of magnitude below that of the magnetic field. If then a weapon is completely encased in a conducting material the internal components of the weapon will not be affected by radar. The split transformer, however, provides a method of communication which, while not very efficient, has been demonstrated to be quite feasible from an energy transfer, reliability and size viewpoint.

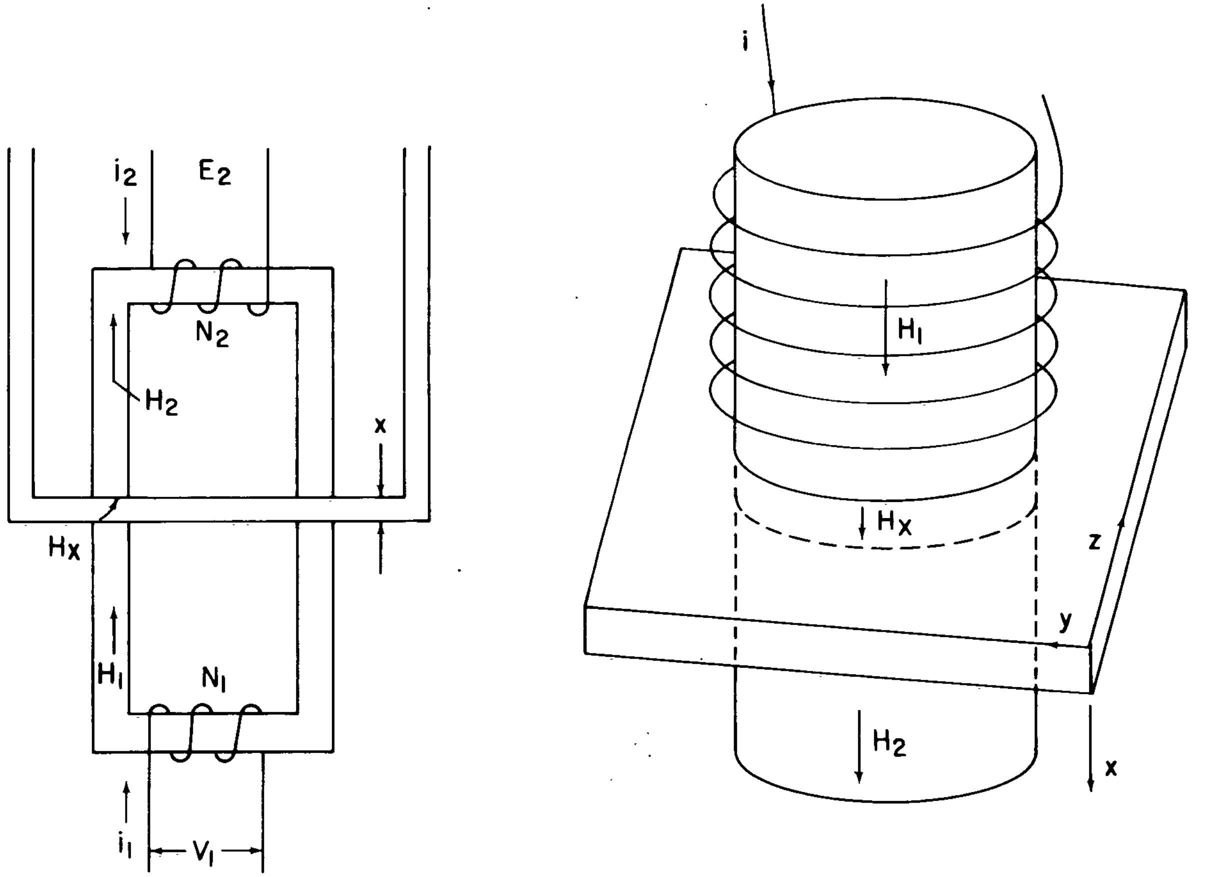

FIG. I (A) SHIELDED MAGNETIC COUPLER (B) APPROXIMATION TO SEMI INFINITE PLANE

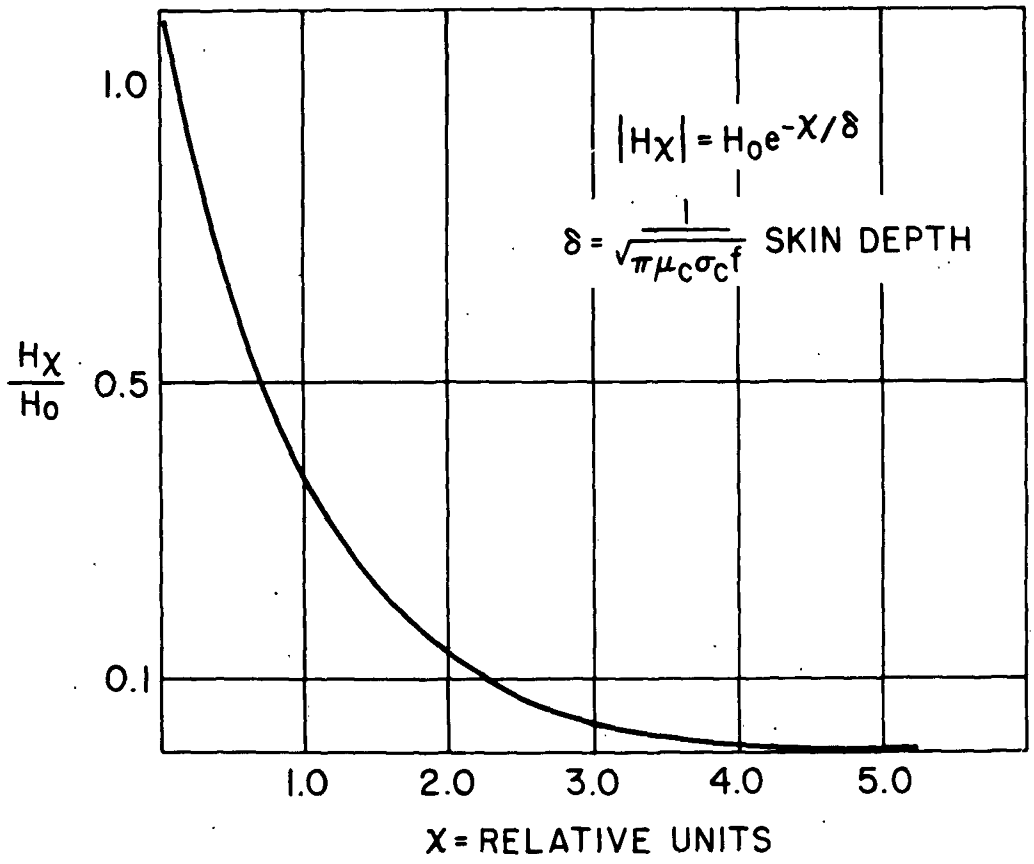

FIG. 2 MAGNETIC FIELD ATTENUATION IN COPPER

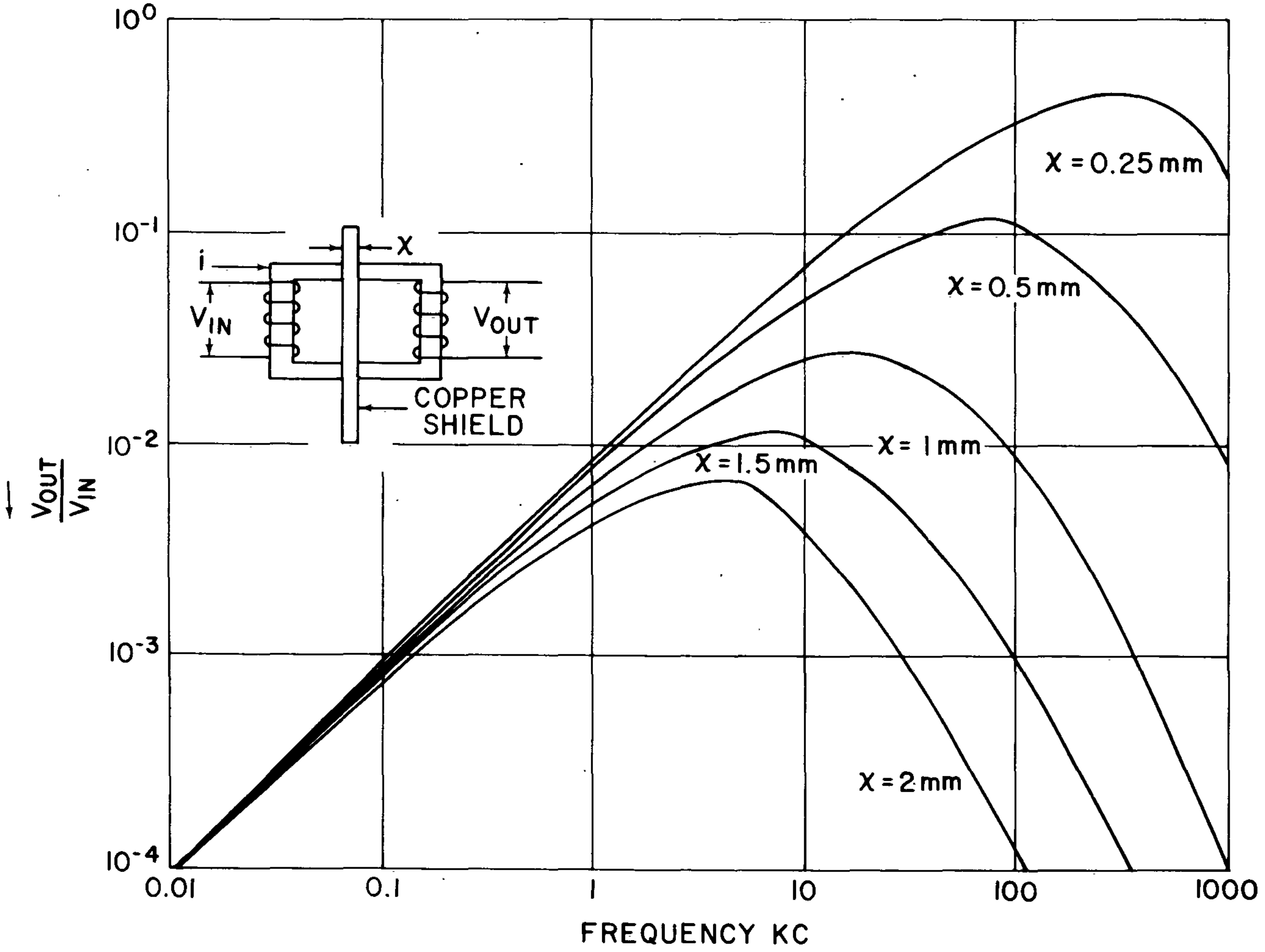

FIG. 3 THEORETICAL V_{OUT} / V_{IN} VERSUS FREQUENCY AS A FUNCTION OF SHIELD THICKNESS

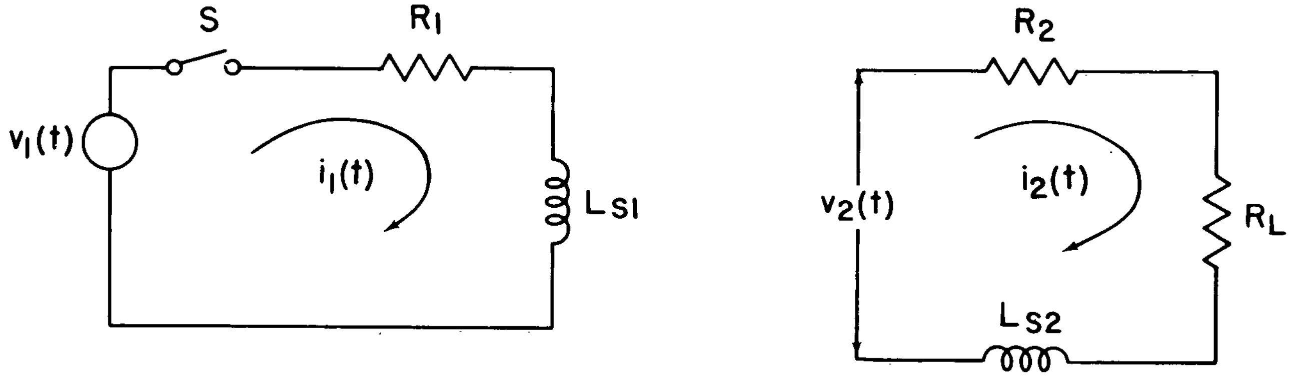

FIG. 4 INPUT AND OUTPUT EQUIVALENT CIRCUITS

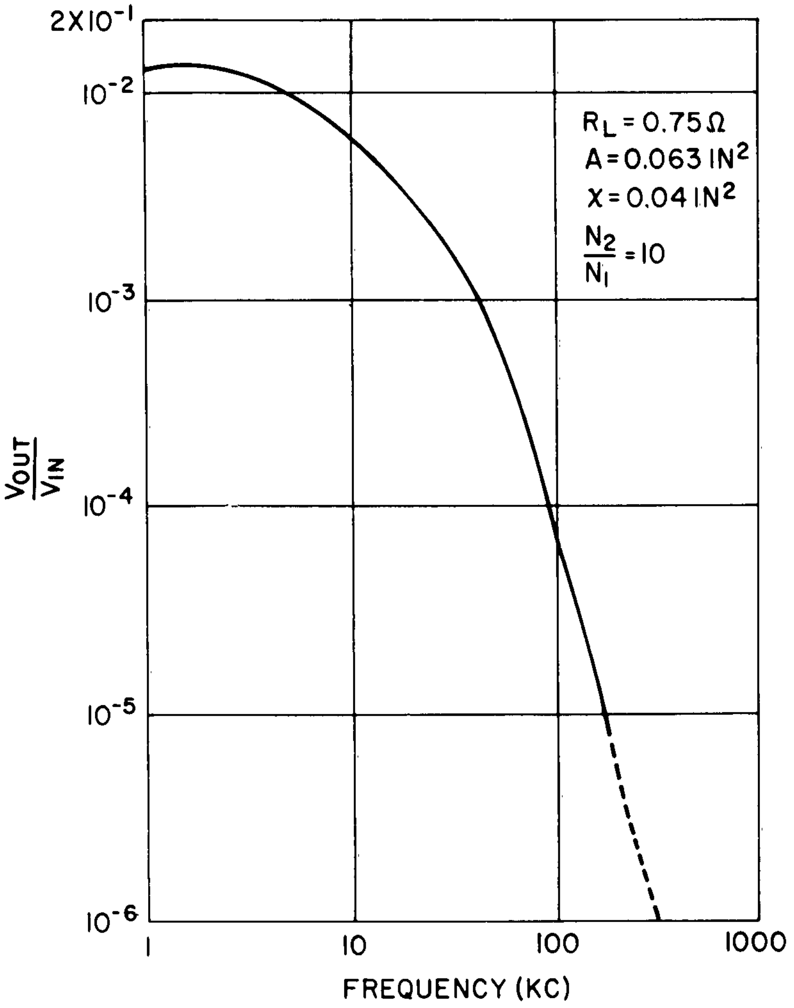

FIG. 5 V_{OUT}/V_{IN} VS FREQUENCY OF EXPERIMENTAL MODEL

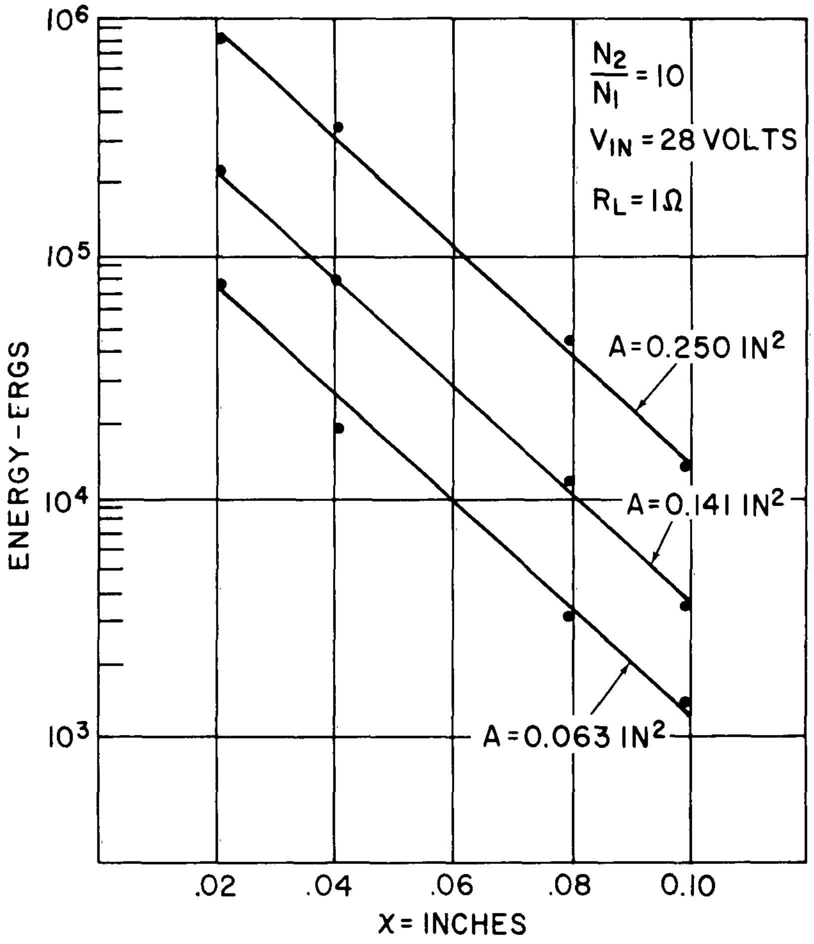

FIG. 6 TRANSMITTED ENERGY VS SHIELD THICKNESS

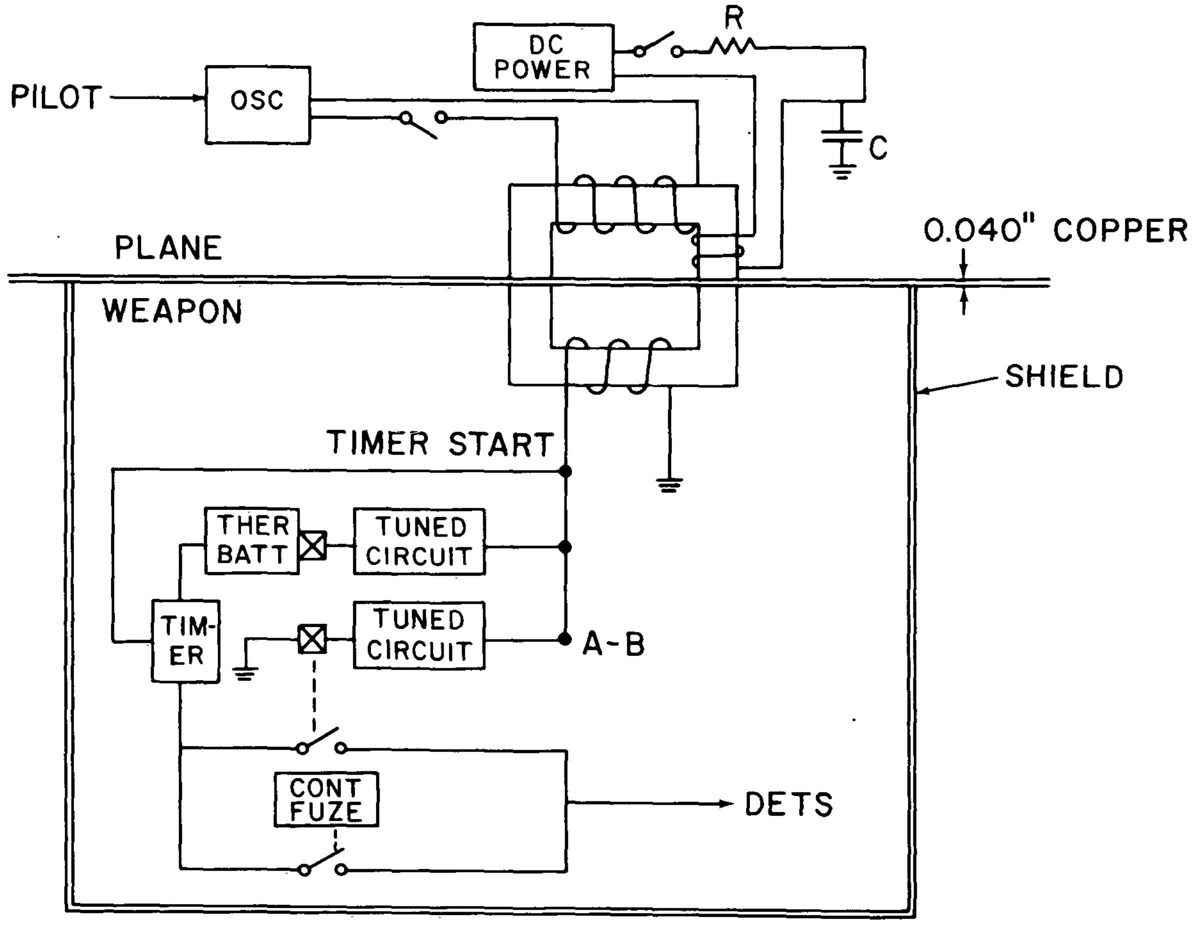

FIG. 7 PLANE TO WEAPON COMMUNICATION BY TUNED CIRCUITS

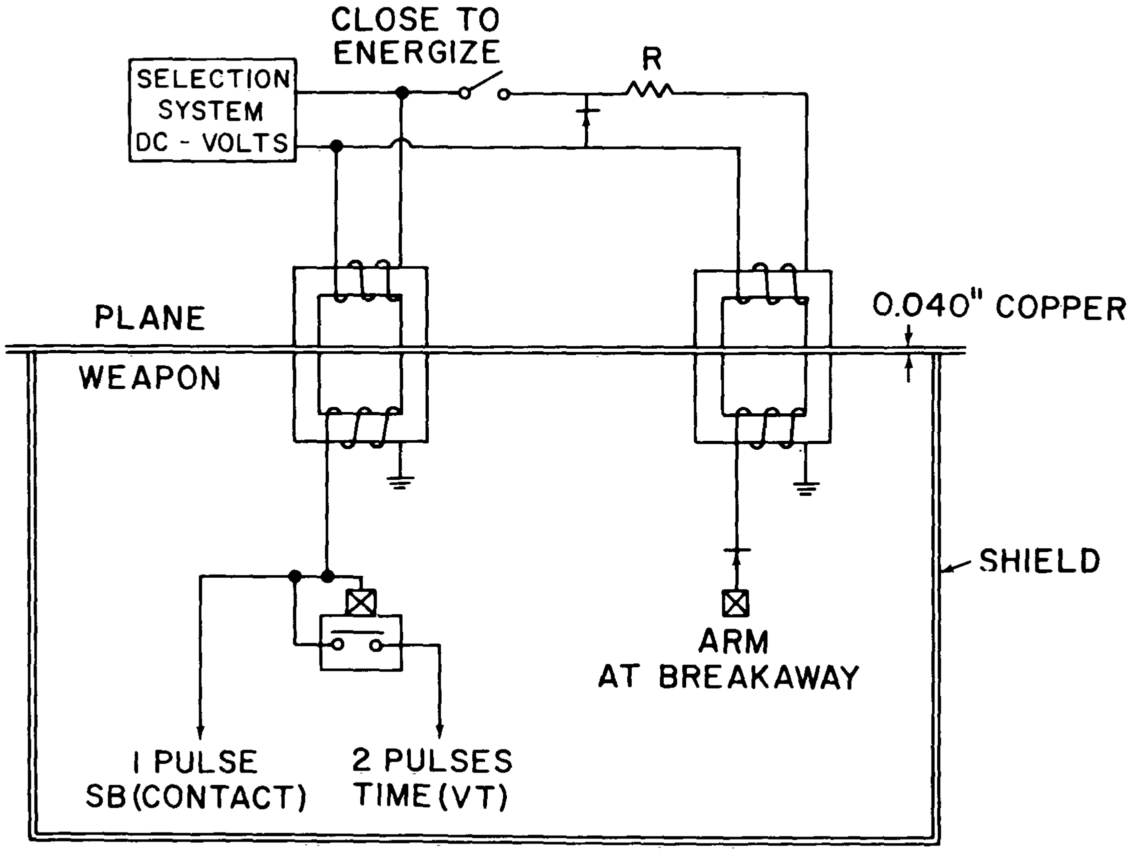

FIG. 8 PLANE TO WEAPON COMMUNICATION BY PULSED SIGNAL

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SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Radiation	RADT	Weapon	WEAP	Step	STEP
Hazards	HAZA	Radiofrequency	RADF	Function	FUNC
Magnetic	MAGC	Input	INPU	Theory	THEY
Coupling	COUP	Output	OUTP	Experiment	EXPE
Shielded	SHIL	Circuits	CIRC	Energy	ENER
Transformer	TRAF	Voltage	VOLT	Electrical	ELEC
Low frequency	LOWF	Frequency	FREQ	Transfer	TRAE
Band pass	BANP	Thickness	THIC	Iron	IRON
Filter	FILT	Electromagnetic	ELEM	Copper	COPP
Communication	COMU	Magnetic field	MAGI	Metals	META
Link	LINK	One-dimensional	ONED	Attenuation	ATTE
Aircraft	AIRC	Sinusoidal	SNEZ		

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(NOL technical report 63-55)
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This report is intended to show the effectiveness of a properly shielded transformer as a low frequency band pass filter, which could easily be adapted as a RADHAZ proof aircraft-weapon communication link.

1. Transformers - Radiation effects
2. Weapons - Radiation effects
3. Radiation - Hazards

I. Title
II. White, Edward A.
III. Project

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