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THE INFLUENCE OF CAPACITOR BANK PARAMETERS ON MAGNETICALLY DRIVEN FLYER PLATES

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ABSTRACT

This memorandum describes the effect of varying capacitor bank parameters on the performance of magnetically driven flyer plates. The equations relating magnetic impulse to bank parameters are derived and some typical curves presented. It is shown that the slow, high-energy bank, though less efficient, is capable of producing equally sharp and ultimately greater impulses than the fast, low-energy bank.

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Introduction

The use of capacitor banks in simulation testing at Livermore Laboratory has been confined primarily to two types of application -- magnetically driven flyer plates (electromagnetic propulsion) and exploding foils. Each requires the delivery of a predictable amount of energy in a very short time. The instantaneous pressure exerted on a flyer plate and the energy delivered to an exploding foil are each proportional to the square of the discharge current. The momentum acquired by a flyer and the energy imparted to a foil are found by integrating the square of the current with respect to time. In each case, the signature of the current delivered to the load determines the effectiveness of the energy transfer.

The time required for the discharge current to reach a particular level is determined by the circuit parameters and the initial bank voltage. In flyer plate testing, the circuit parameters are relatively invariant with respect to time, while in exploding foil experiments the phase changes of the foil result in a highly nonlinear discharge.

It is the purpose of this study to examine the relation of capacitor bank parameters to flyer plate performance only. A typical parallel flyer plate assembly is shown in Figure 1.

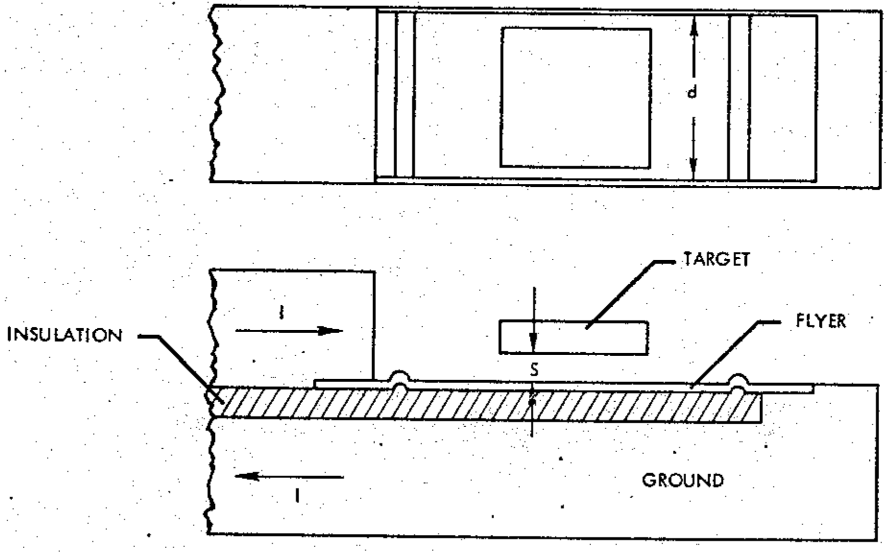

Figure 1. Typical Parallel Flyer Plate Assembly

Theory

The quantity which perhaps best describes the effect of a flyer plate of given thickness as it strikes its target is the momentum density. This quantity is commonly expressed in taps, a unit equivalent to the cgs unit of momentum density (dyn-s/cm^2).

The momentum density acquired by a flyer plate as a function of capacitor bank parameters may be easily estimated by making certain simplifying assumptions. If it is assumed that the circuit is a series R-L-C network with time invariant elements, the current and, consequently, the pressure exerted on the flyer may be determined. If the inductance and resistance of the flyer are small compared to those of the bank, the current is a damped sine function and is relatively unaffected by the motion of the flyer.

Flyer motion primarily affects the inductance term in the equations. It causes an increase in inductance which limits the current and causes the natural frequency of the discharge to decrease. At extremely high current densities flyer heating causes a nonlinear resistance change, complicating the equations. However, if the current has decayed sufficiently by the time the flyer has moved an appreciable distance, and if the bank impedance is sufficiently high, the parameters in the following equations may be considered to remain constant.

The magnetic flux density in the region separating narrowly spaced, parallel plates carrying oppositely directed currents is essentially that of the infinte plate case if the spacing is small compared to the length and width of the plates. It is given as

$$B = \frac{\mu I}{d} \text{ Wb/m}^2 \qquad (1)$$

where $\mu = 4\pi \times 10^{-7}$ H/m

I = Total current (A)

d = Flyer width (m)

The instantaneous pressure exerted on the plates tends to separate them and is given as

$$P = \frac{1}{2} \frac{B^2}{\mu} \text{ N/m}^2$$

or, by substituting Equation (1) for B,

$$P = \frac{1}{2} \frac{\mu I^2}{d^2} \qquad (2)$$

The quantity <u>magnetic pressure impulse</u>, which is a measure of the momentum density of the flyer, may be obtained by integrating Equation (2) with respect to time:

$$M = \int_0^t P(t)\, dt \qquad (3)$$

The current associated with the discharge of a capacitor bank through a magnetic flyer plate is typically the damped sine wave associated with a series R-L-C circuit:

$$I = \frac{V}{\omega L} \exp(-at) \sin \omega t \qquad (4)$$

where

$$a = \frac{R}{2L}$$

and

$$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

R, L, and C are the series resistance, inductance, and capacitance (assumed to be constant) and V is the initial capacitor voltage. Substituting Equation (4) into Equation (2) yields an expression for the instantaneous pressure. This expression may be substituted into Equation (3) to obtain the impulse as a function of time and the circuit parameters:

$$M(t) = \frac{\mu}{2d^2} \left(\frac{V}{\omega L}\right)^2 \int_0^t (\exp(-2at) \sin^2 \omega t)\, dt \qquad (5)$$

or

$$M(t) = \frac{\mu}{8d^2} \left(\frac{V}{\omega L}\right)^2 \left[\frac{1 - \exp(-2at)}{a} - \frac{(\omega \sin 2 \omega t - a \cos 2\omega t)\exp(-2at) + a}{a^2 + \omega^2} \right] \qquad (6)$$

When $t = \frac{2}{a}$, the impulse is nearly at its final value,

$$M(t = \frac{2}{a}) \doteq \frac{\mu}{8d^2} \left(\frac{V}{\omega L}\right)^2 \left(\frac{\omega^2}{a (a^2 + \omega^2)} \right)$$

which reduces to

$$M = \frac{\mu E}{2d^2 R} \quad \text{N-s/m}^2 \tag{7}$$

where

$$E = \frac{1}{2} CV^2$$

is the initial bank energy in joules. If d is expressed in centimeters and the permeability is that of free space, Equation (7) may be written

$$M\left(\frac{2}{a}\right) \doteq \frac{0.063\ E}{d^2\ R} \quad \text{taps} \quad (\text{dyn-s/cm}^2)$$

Results

If the transit time of the flyer plate is less than 2/a, Equation (6) must be used to calculate the magnetic impulse. Examination of this equation shows it to be a monotonically increasing function. The initial value is zero and increases toward the final value given by Equation (7) in a quasi-exponential manner. Typical curves are shown in Figure 2. It should be noted that the magnetic impulse is normalized with respect to the inverse square of capacitor bank voltage and the direct square of flyer plate width.

The transit time of the flyer plate, which defines the time scale of the experiment, may be estimated from the equation,

$$t = \frac{S}{v/2}$$

where t is the transit time, v/2 is the approximate average velocity, and S is the distance to the target. Typical final velocities are of the order of

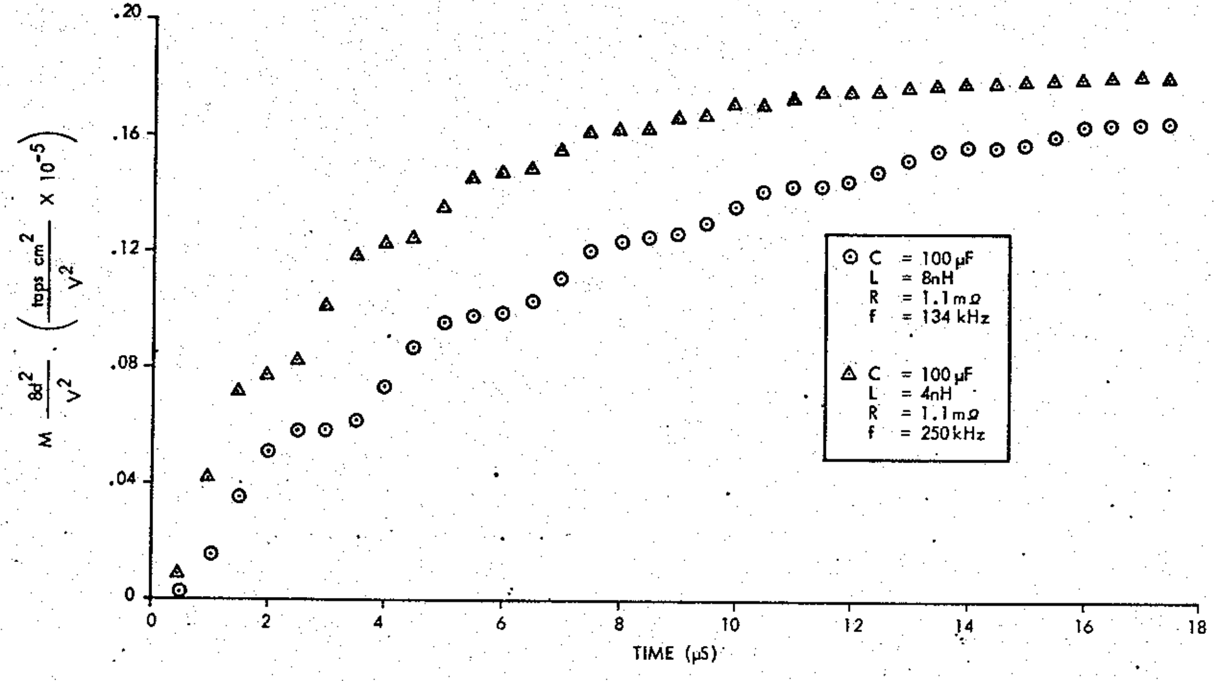

Figure 2a. Normalized Magnetic Impulse: Effect of Doubling Inductance

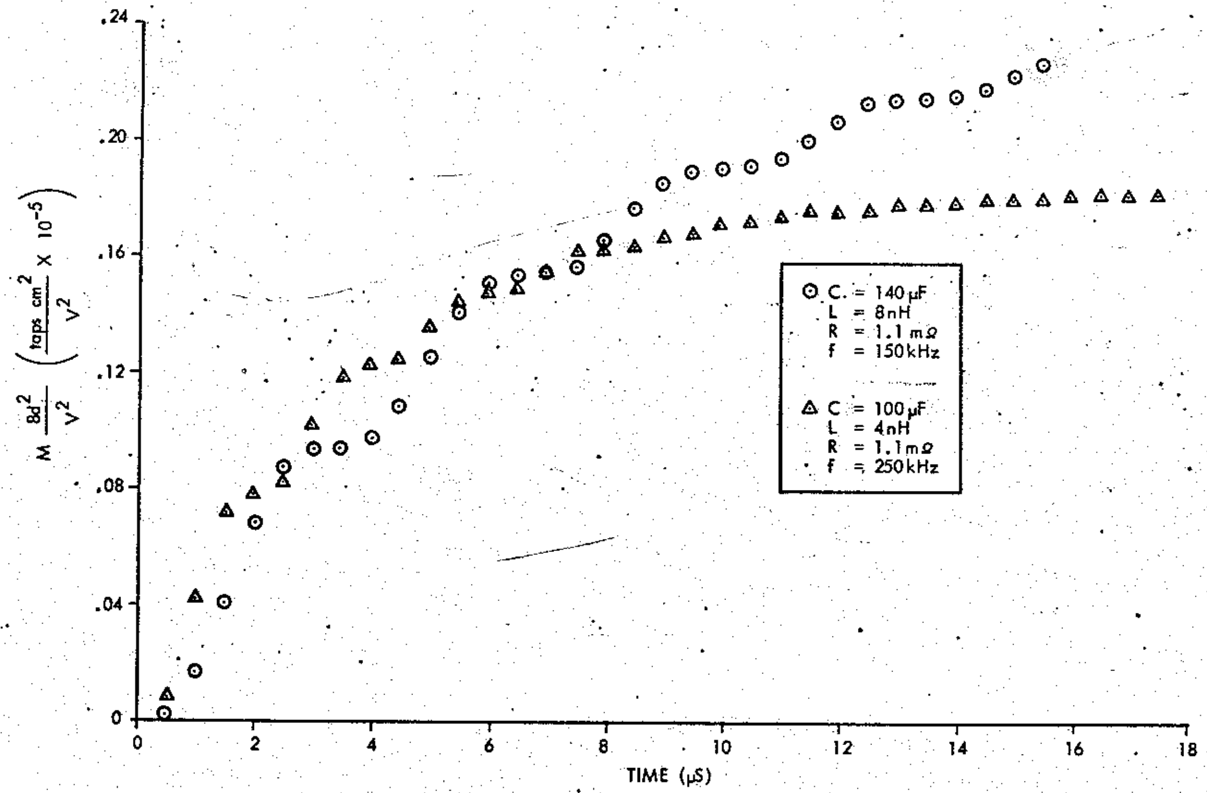

Figure 2b. Normalized Magnetic Impulse: Effect of Increasing Both Inductance and Capacitance

0.05 to 0.1 centimeters per microsecond, while the distance to the target is usually in the neighborhood of 100 mils. Hence, in comparing the curves of magnetic impulse, one must focus attention on times in the neighborhood of five to ten microseconds.

Voltage and inductance are trade-off parameters in capacitor bank design. Higher voltages yield higher maximum impulses but, because they require more space between conductors, result also in a higher inductance and a slower rise to the maximum value. Lower inductances yield a faster rise but require a reduction of space between conductors and the use of a lower voltage.

Figure 2a shows the advantage of a lower inductance bank. Though both curves rise to approximately the same maximum value, the lower inductance curve rises faster and is at a higher level at an earlier time than the higher inductance curve. The final value of the magnetic impulse, however, is independent of inductance and proportional to the square of voltage. If, for example, the voltage for the higher inductance curve were increased by about forty percent, the curve would lie above the lower inductance curve after one microsecond and would have a final value twice that of the lower inductance curve. Thus the adverse effect of higher inductance may be overcome by a sufficient increase in voltage.

The final value of the magnetic impulse may also be raised by increasing capacitance. Figure 2b shows the result of a forty-percent increase in capacitance with a 100-percent increase in inductance. For times greater than five microseconds, the 140-microfarad impulse is equal to or greater than the 100-microfarad impulse. The final impulse is forty percent greater.

The effect of varying resistance has not been shown in the above curves, although it would have been more realistic to do so. Resistance is a function of frequency, i.e., is roughly proportional, as determined by the skin effect phenomenon, to the square root of frequency. Since the skin depth of conductors at the frequencies of concern is small compared to the thickness of typical transmission lines and is of the same order as typical flyer plate thicknesses, one would expect total resistance to be somewhat lower for lower frequency discharges. Thus the discharge associated with a higher inductance should have the advantage of slightly lower resistance.

Conclusions

A given amount of momentum may be imparted to a magnetically driven flyer plate in a short time most efficiently by using a fast, low-energy capacitor bank. The same momentum may be imparted in a comparable time, although less efficiently, by using a slow, high-energy bank. The difficulty and expense of achieving the ultra-low inductance required by a fast, low-energy bank may therefore be overcome by using a slow, high-energy bank and settling for a lower degree of efficiency. This alternative will give equally sharp and ultimately greater impulses. Thus it appears that, for flyer plate work, the choice of increasing voltage at the expense of efficiency is preferable to that of attempting to achieve very low inductance.

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