GUIDELINES FOR THE DESIGN OF SYNCHRONOUS-TYPE COILGUNS

E. Levi, J. L. He, Z. Zabar, and L. Birenbaum
Polytechnic University
333 Jay Street
Brooklyn, New York

Abstract

Smooth acceleration and evenly distributed mechanical and thermal stresses can be achieved in a coilgun type of electromagnetic launcher by the interaction between an electromagnetic wave-packet traveling along the barrel and a moving cylindrical conductor (sleeve) carrying a system of currents. The barrel consists of an array of cylindrical coils energized by polyphase currents; upon the sleeve is impressed a sinusoidal distribution of azimuthal currents.

Design guides and scaling laws are developed for such a launcher. It is shown that muzzle velocities up to 10 km/s might be attainable with a barrel length of less than 15 m with high efficiencies. However, for velocities far in excess of that range, the need to maintain the physical integrity of solid armatures leads to barrel lengths which may be impractical for most applications.

1. Introduction

Electromagnetic launchers, or EML's, can in principle accelerate massive bodies to velocities far in excess of those attainable with conventional guns which utilize chemical energy.

EML's are essentially linear electric motors and hence may be classified as either homopolar, in which the polarity of the magnetic field does not vary, or heteropolar in which the polarity alternates. To the first class belongs the railgun, which consists of an electrical circuit containing an energy source, a switch, two parallel rails (the barrel), and an armature (the projectile), which slides between them. To the second class belongs the coilgun, in which barrel and projectile consist of mutually coupled coils.

Most of the development to date has been concentrated on railguns. The main reasons are the simplicity of the electrical circuit and the ease in energization. Against these advantages must be weighed the need for sliding contacts between the rails and the armature with consequent presence of friction, arcing and erosion. Also, in the simplest case of constant current with supply at the breech, the energy acquired by the projectile in kinetic form cannot exceed the energy left behind in magnetic form. Therefore, the efficiency cannot exceed 50 percent. Although this last drawback can be overcome by distributing the energy sources along the length of the rails, the power conditioning becomes complex, as it is for the coilgun. The latter type, being based on inductive coupling, offers the advantage of a contactless energy transfer to the projectile, and also of the distribution of the thrust over a larger surface, with consequent reduction in the mechanical stresses [1-7].

General relationships which may apply to both coilguns and railguns are derived in the next section. Section 3 introduces an idealized coilgun model which provides the basis for design and for determination of the main dimensions. Departures from this idealized model and their effects on performance are treated in Section 4. Concluding remarks complete the paper.

2. General Relations

Ideally, an electromagnetic launcher should be designed to achieve a given muzzle velocity using as short a barrel as possible. This means that the acceleration and the thrust should be as high as possible, consistent with the strength of the materials. As will be shown, these requirements translate into accelerations approaching half a million times that of gravity. For comparison, the antitank copperhead shell is subjected to accelerations of only 9000 g's.

The armature of the projectile is subjected to mechanical, electromagnetic, and thermal stresses which are impulsive in character. Therefore, in order to separate their effects, it is useful to determine the order of magnitude of the speed with which each stress propagates. Mechanical stresses propagate with the velocity of sound which, in solids, is in the order of (10^3) m/s. Since the materials of interest are good conductors, the propagation of electromagnetic and thermal stresses is governed by diffusion equations. Introducing a characteristic length L which is typically in the order of 1 cm one can write for the diffusion velocity

$$v_d = \alpha / L \tag{1}$$

where α is the diffusivity. Denoting by γ the electrical conductivity and by μ the magnetic permeability, one obtains for the diffusivity of the electromagnetic stress

$$\alpha_{e,m} = \frac{1}{\gamma\mu} = O\left(10^{-2}\right) \quad m^2/s \tag{2}$$

This corresponds to a velocity of 1 m/s. Denoting by $\lambda(Wm^{-1}K^{-1})$ the heat conductivity and by c the specific heat per unit volume, one obtains for the thermal diffusivity

$$\alpha_t = \frac{\lambda}{c} = O\left(10^{-4}\right) \quad m^2/s \tag{3}$$

corresponding to a velocity of 10^{-2} m/s.

The large differences in the propagation velocities of the mechanical, electromagnetic, and thermal stresses thus suggest that one can assume that the mechanical stresses are established instantaneously, that the electrical stresses are established next, and last, that all the heat is dissipated in one skin depth and is absorbed locally; that is, the thermal process is adiabatic.

These considerations permit some general relationships to be derived by considering a unit volume of the projectile armature. Let $\underline{J}$ denote the current density, $\underline{B}$ the magnetic flux density, ξ the mass density of the armature conductor, ν the ratio of the overall mass of the projectile to the mass of the armature conductor, and θ the temperature rise over the ambient. If one neglects friction losses, the increment of kinetic energy from the breech velocity v_b to the muzzle velocity v_m equals the work done by the electromagnetic force $\underline{J} \times \underline{B}$ over the length l of the barrel or

$$\Delta w_{kin} = \frac{1}{2} \nu\xi \left(v_m^2 - v_b^2\right) = \int_o^l \underline{J} \times \underline{B} \cdot d\underline{l} \quad J/m^3 \tag{4}$$

0018-9464/91/0100-0628$01.00 © 1991 IEEE

The energy dissipated in the conductor is

$$w_{diss} = \frac{J^2}{\gamma} \cdot \frac{l}{(v_m + v_b)/2} = c\theta \quad J/m^3 \tag{5}$$

In the ideal case of uniform current distribution and perpendicular orientation of the vectors $\underline{J}$, $\underline{B}$, and $d\underline{l}$ one can eliminate $\underline{J}$ and obtain:

$$\left(v_m^2 - v_b^2\right)\left(v_m - v_b\right) = \frac{2\gamma c\theta B^2}{\nu^2\xi^2} l \tag{6}$$

where B should be assigned an average value.

It appears that in the limit $v_b \to 0$, the length l of the barrel increases as the cube of the muzzle velocity. One can now arrive at an estimate of the numerical values by relating the maximum allowable mechanical stress σ_m (N/m^2) to the force acting on a unit surface of the armature conductor. Letting

$$\sigma_m = K_p B = \frac{B^2}{\varepsilon\mu_o} \tag{7}$$

where K_p is the surface current density (A/m) of the armature conductor and ε is a non-dimensional factor, which depends on the geometry, and is always less than 1/2, one obtains

$$v_m = \left(\frac{2\gamma c\theta\varepsilon\mu_o\sigma_m}{\nu^2\xi^2} l\right)^{1/3} \tag{8}$$

Contemplating the use of hard drawn, oxygen-free copper, as armature material, allowing a temperature rise θ = 800 K, i.e. about 80% of the melting temperature and letting

$$\begin{aligned} \sigma_m &= 2.5\times10^8 \text{ Pa} \\ \xi &= 8.93\times10^3 \text{ kg/m}^3 \\ \gamma &= 10^7 \text{ S/m} \\ c &= 3.47\times10^6 \text{ JK}^{-1}\text{ m}^{-3} \\ \varepsilon &= 0.35 \end{aligned}$$

Equation (8) yields:

$$v_m = 4.26\times10^3\left(\frac{l}{\nu^2}\right)^{1/3} m/s \tag{9}$$

so that for v_m = 10 km/s and ν = 1 the length of the barrel is 12.93 m. This corresponds to an average acceleration of 3.86×10^6 m/s^2 or 3.94×10^5 g's.

Considering that the ideal condition of uniform current distribution is difficult to attain, because of the skin effect [8], it appears that with a solid armature, it will be difficult to achieve velocities far in excess of 10 km/s. This, however, is quite adequate for endo-atmospheric applications, because, due to the resistance of the air, the nose of the projectile would melt for velocities in excess of about 8 km/s, unless it was protected by ablative cones.

Once the length of the barrel has been determined, it becomes possible to find the thickness a_p of the armature conductor from

$$K_p = a_p J = \frac{\sigma_m}{B} \tag{10}$$

Making use of Eqs. (4), (6) and (7) this turns out to be

$$a_p = \sigma_m \frac{l}{\Delta w_{kin}} = \frac{\nu}{\varepsilon}\frac{\xi(v_m - v_b)}{\mu_o\gamma c\theta} \tag{11}$$

Introduction of the values for the copper conductor yields

$$a_p = 2.56\frac{\nu}{\varepsilon}(v_m - v_b)\times10^{-7} m\,. \tag{12}$$

The thermal limitation also imposes a lower limit on the efficiency with which the gun must operate. If W_{kin} denotes the kinetic energy of the projectile at the muzzle, then the volume of the armature conductor is

$$Volume = \frac{W_{kin}}{\frac{1}{2}\nu\xi v_m^2} \tag{13}$$

and the total ohmic loss in the projectile armature is

$$W_{diss}^p = c\theta\,(Volume) = c\theta\frac{W_{kin}}{\frac{1}{2}\nu\xi v_m^2} \tag{14}$$

If ζ denotes the ratio of the total ohmic loss W_{diss}^{p+b} including the barrel to that of the projectile armature, one can write

$$W_{diss}^{p+b} = 2\zeta c\theta\frac{W_{kin}}{\nu\xi v_m^2} \tag{15}$$

and, since in the case of distributed energy sources the ohmic loss is the dominant one, the efficiency of the gun can be estimated as

$$\eta = \frac{1}{1 + W_{diss}^{p+b}/\Delta W_{kin}} \tag{16}$$

where ΔW_{kin} is the kinetic energy gained by the projectile in the barrel.

For the example previously considered and assuming ζ = 5, ν = 2, and $W_{kin}/\Delta W_{kin}$ = 1.1, one obtains

$$\eta = \frac{1}{1 + 1.71\times10^6/v_m^2} \tag{17}$$

As could be expected, because of the large counter e.m.f., and as is the case with all motors, the efficiency increases with the velocity. For a muzzle velocity v_m = 10 km/s, the efficiency is 98%. Moreover, the efficiency is independent of the mass.

In conclusion, EML's must be designed to operate at high efficiencies if the armature is to remain in the solid state.

3. Idealized Model of Coilgun

The force acting on the coil guiding the projectile in the single stage (two coils) coilgun has an effective range of less than one coil diameter [5]. Replacing the barrel length l by the diameter, and assuming a typical diameter of 5 cm, Eq. (9) with ν = 1 yields $v_m = 1.57\times10^3$ m/s.

To attain higher velocities one needs a multistage arrangement in which the barrel consists of an array of coils energized synchronously with the progression of the projectile. Also, the motion of a single projectile coil might be expected to be unstable against lateral diversion and tumbling. Therefore, more than one coil is needed also in the projectile.

Another important consideration is that, in view of the limitations imposed by the strength of the materials, the stresses should be distributed as evenly as possible both in space and time.

A coilgun arrangement which satisfies these requirements is shown in Fig. 1. The barrel coils are energized in a polyphase fashion, so as to create a traveling electromagnetic wave packet of limited extent. Similarly, the discrete coil in the projectile is replaced by a continuous tubular conductor (sleeve) of sufficient length to accommodate a number of wavelengths. The thrust then results from the interaction of two systems of length to accommodate a number of wavelengths. The thrust then results from the interaction of two systems of azimuthal currents sinusoidally distributed in the longitudinal direction. The currents in the sleeve are impressed in the first stage of the barrel and the sleeve thickness must be chosen so that the time it takes them to decay is longer than the transit time T of the projectile in the barrel.

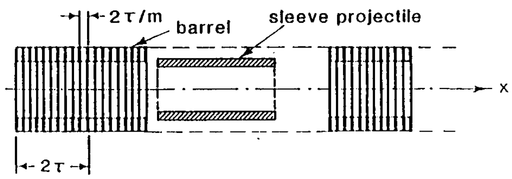

Fig. 1 Polyphase barrel with sleeve projectile

The design of the coilgun can now be based on the idealized model used in conventional electrical machines. The actual current distributions in the barrel and in the sleeve are reduced to surface current sheets by letting the thickness of the conductor vanish. Also, in most cases of practical interest, one can neglect the curvature of the conductors and deal with planar sheets [8]. Thus, one arrives at the model shown in Fig. 2.

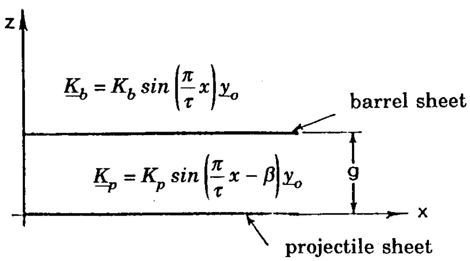

Fig. 2 Planar sheet model of coilgun

In the wave frame, that is, a frame attached to the projectile, the current distributions are:

$$\underline{K}_b = K_b \sin\left(\frac{\pi}{\tau}x\right)\underline{y}_o \tag{18}$$

in the barrel, and

$$\underline{K}_p = K_p \sin\left(\frac{\pi}{\tau}x - \beta\right)\underline{y}_o \tag{19}$$

in the projectile, where τ is the pole pitch.

By solving Maxwell's equations, one finds that the field produced by $\underline{K}_b$ in the plane of the sleeve located at an equivalent distance g is given by:

$$H_{bx} = -\frac{K_b}{2}\sin\left(\frac{\pi}{\tau}x\right)e^{-\frac{\pi}{\tau}g} \tag{20}$$

$$B_{bz} = \mu_o\frac{K_b}{2}\cos\left(\frac{\pi}{\tau}x\right)e^{-\frac{\pi}{\tau}g} \tag{21}$$

The local value of the force per unit surface acting on the sleeve located at a distance g is then

$$\begin{aligned}\underline{f}_p &= \underline{K}_p \times \underline{B}_b \\ &= \mu_o K_p \frac{K_b}{2}e^{-\frac{\pi}{\tau}g}\sin\left(\frac{\pi}{\tau}x - \beta\right)\cdot \\ &\quad\cdot\left[\cos\left(\frac{\pi}{\tau}x\right)\underline{x}_o + \sin\left(\frac{\pi}{\tau}x\right)\underline{z}_o\right]\end{aligned} \tag{22}$$

and its average value is

$$\langle \underline{f}_p\rangle = -\mu_o K_p\frac{K_b}{4}e^{-\frac{\pi}{\tau}g}\left(\sin\beta\,\underline{x}_o - \cos\beta\,\underline{z}_o\right) \tag{23}$$

Equating this force density with the maximum allowable stress σ_m gives

$$K_p = \frac{4\sigma_m}{\mu_o K_b}e^{\frac{\pi}{\tau}g} \tag{24}$$

Integrating Newton's law between the breech and muzzle velocities one obtains:

$$\begin{aligned}v\xi\left(v_m - v_b\right) &= \frac{\langle f_p\rangle_x}{a_p}T = \frac{\langle f_p\rangle_x}{a_p}\frac{2c\theta a_p^2\gamma}{K_p^2} \\ &= \frac{\mu_o K_b e^{-\frac{\pi}{\tau}g}\theta a_p\gamma c\sin\beta}{2K_p}\end{aligned} \tag{25}$$

where use has been made of the relations

$$c\theta = \frac{J^2}{\gamma}T = \left(\frac{K_p}{a_p}\right)^2\frac{T}{\gamma}$$

Introducing K_p from Eq. (24), one obtains

$$K_b^2 = \frac{8v\xi\left(v_m - v_b\right)\sigma_m}{\mu_o^2 c\theta\gamma\sin\beta}\frac{1}{a_p e^{-2\frac{\pi}{\tau}g}} \tag{26}$$

The distance g between the equivalent current sheets is a function of the thickness of the barrel and projectile conductors a_b and a_p and is approximately [9]

$$g \sim g_c + \frac{a_b + a_p}{2} \tag{27}$$

where g_c, the clearance between barrel and sleeve, can be kept below 1 mm. Introducing this value of g into Eq. (26), one finds that K_a reaches a minimum value when $a_p = \frac{\tau}{\pi}$, so that Eq. (25) gives

$$\frac{K_b}{K_p} = \frac{\pi}{\tau}\frac{2v\xi\left(v_m - v_b\right)}{e^{-\frac{\pi}{\tau}g}c\theta\mu_o\gamma} \tag{28}$$

where letting $a_b = a_p$ and neglecting g_c

$$\frac{\pi}{\tau}g \sim 1 \tag{29}$$

Solving, instead, Eq. (25) for a_p one obtains

$$a_p = \frac{1}{\left(\frac{e^{-\frac{\pi}{\tau}g}}{2}\frac{K_b}{K_p}\sin\beta\right)}\frac{v\xi\left(v_m - v_b\right)}{\mu_o\gamma c\,\theta} \tag{30}$$

The sleeve thickness thus obtained on the basis of thermal considerations should be checked to verify that it satisfies structural requirements as well.

Comparison with Eq. (11) shows that, for a coilgun, ε is

$$\varepsilon = \frac{e^{-\frac{\pi}{\tau}g}}{2} \frac{K_b}{K_p} \sin\beta \tag{31}$$

It is interesting to compare this value with the corresponding one for a railgun. In that case, one has

$$K_b = K_p = \frac{B}{\varepsilon\mu_o} \tag{32}$$

where in the ideal case of a railgun having a coaxial structure $\varepsilon = 1/2$. With a parallel plate structure one can assume $\beta = 45°$. It follows that, in order to obtain the same thickness a_p in the coilgun as in the railgun, one needs

$$\frac{K_b}{K_p} = \sqrt{2}\, e^{\frac{\pi}{\tau}g} \tag{33}$$

and introducing $(\pi/\tau)\, g \sim 1$

$$\frac{K_b}{K_p} \sim 3.83 \tag{34}$$

Since it would be difficult to accommodate a much larger K in the barrel, while keeping $a_b = a_p$, and since a much larger a_b would increase g and, therefore, decrease the coupling between barrel coils and projectile sleeve, one must conclude from Eq. (30) that the thickness of the moving conductor of the coilgun must be larger than in the railgun. This, combined with the fact that the need for strong coupling sets a lower limit of about two inches for the diameter of the sleeve and that because of stability considerations, it is desirable to accommodate at least one wavelength in the length of the sleeve [5] leads to the conclusion that coilgun projectiles might be much heavier than those in railguns.

4. Departures From the Idealized Model

It can be shown that, even with a bore diameter as small as is practical, the effect of the curvature of the conductors can be neglected and that their finite thickness can be taken into account by introducing an equivalent distance g between the two current sheets [9].

More important are: (1) the finite length of the barrel coils; (2) the end effects due to the finite lengths of the current sheets both in the barrel and in the sleeve; and (3) the fact that since the electromagnetic wave packet is traveling along the barrel with increasing velocity, while the velocity of the sleeve is constant over its own length, only one cross-section of the sleeve can progress in synchronization with the wave packet.

With an endless array of coils, as is the case in rotating machines, the nonvanishing width of the coils and the consequent finite number of phases m would give rise to a line spectrum of harmonics of order $\nu = k_1 + 1$ where k_1 is any positive or negative integer including zero. Due to the finite length of the barrel, however, the line spectrum of space harmonics broadens into a continuum. Similarly, the limited extent of the wave packet and the consequent finite duration of the excitation of each coil give rise to a continuum of time harmonics.

If each coil is represented by a current sheet that extends over a space interval equal to its width $2\tau/m$, and if its surface current density K_b is assumed to vary sinusoidally in time with period T_o over a time interval nT_o, then the Fourier integral representation in terms of the wavenumber k and the angular frequency ω is:

$$K_b(x,t)_1 = \frac{K_b}{\pi^2}\int_{0+}^{\infty} d\omega \int_{0+}^{\infty} \frac{\sin\frac{\tau}{m}k}{k}\left[\frac{\sin\left(\frac{2\pi}{T_o}-\omega\right)\frac{nT_o}{2}}{\frac{2\pi}{T_o}-\omega} - \frac{\sin\left(\frac{2\pi}{T_o}+\omega\right)\frac{nT_o}{2}}{\frac{2\pi}{T_o}+\omega}\right] \cdot\left[\sin(\omega t - kx) + \sin(\omega t + kx)\right] dk \tag{35}$$

Taking into account that adjacent coils are displaced by a space interval $2\tau/m$ and their sinusoidal currents are delayed by a time interval T_o/m, the combined excitation of the w coils in the barrel is found by replacing the last factor in the integral of Eq. 35 with

$$\left\{\begin{array}{l} k^{+}_{k,\omega}\sin\left[\omega t - kx - (w-1)\left(\frac{\omega T_o}{2m} - \frac{k\tau}{m}\right)\right] \\ + k^{-}_{k,\omega}\sin\left[\omega t + kx - (w-1)\left(\frac{\omega T_o}{2m} + \frac{k\tau}{m}\right)\right] \end{array}\right\}$$

where

$$k^{\pm}_{k,\omega} = \frac{\sin w\left(\frac{\omega T_o}{2m} \mp \frac{k\tau}{m}\right)}{\sin\left(\frac{\omega T_o}{2m} \mp \frac{k\tau}{m}\right)} \tag{36}$$

It is difficult to evaluate $K_b(x,t)$ analytically, because contour integration is not feasible. Numerical integration is equivalent to the performance of Fourier series analysis over arbitrary repetitive patterns in space and time, such that the new pole pitch is $r\tau$ and the new period is pT_0. As a result, the integration intervals in space and time become $\Delta k = \pi/(r\tau)$ and $\Delta\omega = (2\pi)/(pT_0)$ respectively.

Several conclusions can be drawn by observing that the various factors in the integrand of Eq. 35 are of the (sin x)/x type and peak at $k = 0$, $\omega = 2\pi/T_0$, and $\omega = (2m\pi a)/T_0 \pm (2k\tau)/T_0$, where a is any positive integer including zero. The peaks become more sharply defined and the relative amplitude of the fundamental becomes larger with increasing number of phases m, total number of coils w and number of periods n of the current excitation.

The spectral distribution for a typical case with m = 6, w = 396, and n = 3 is shown in Fig. 3 for the forward waves. The backward waves have a similar spectrum with the signs of the amplitudes interchanged. Here, s and q denote the orders of the space and time harmonics respectively, r = 198, and p = 12. It appears that the most significant peaks result from the zeros in the denominator of $k^{\pm}_{k,\omega}$. Those for which a = 0 correspond to waves traveling with the same phase velocity $\omega/k = 2\tau/T_0$ as the fundamental and, in the case that the projectile travels at synchronous speed, do not induce currents in the sleeve. Moreover, because of the ortogonality of the sinusoidal functions, they do not produce a net force if the current impressed on the sleeve contains an integer number of wavelengths.

The peaks resulting from the zeros in the denominator of $k^{-}_{k,\omega}$ correspond to waves traveling in the opposite direction of the projectile. These waves induce currents in the sleeve and give rise to a braking action. Even though their amplitude approaches, and in the case of the fifth space harmonic, reaches that of the fundamental, their effect is relatively small, because they couple only weakly with the sleeve. The reason is

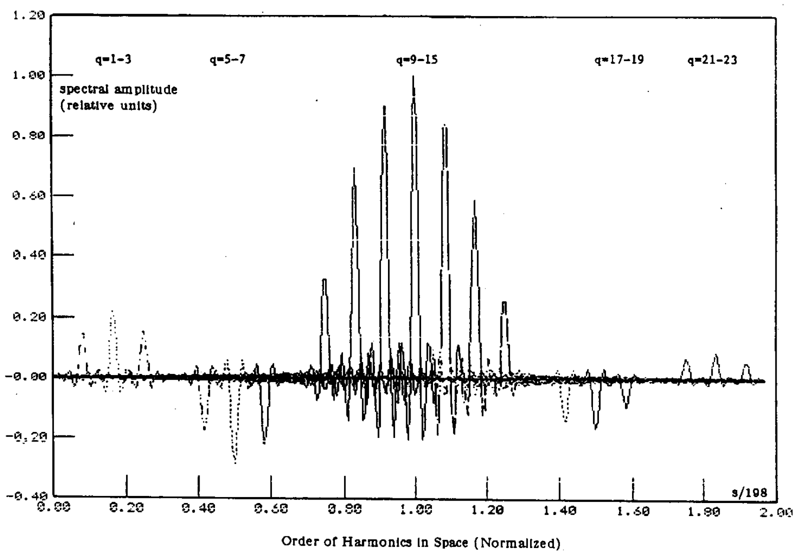

Fig. 3 Spectral composition of forward traveling waves

two fold. First, their half-wavelength is a small fraction of τ and, according to Eq. (21), the B_z field decays exponentially with the order of the harmonic. Second, their high values of slip result in strong skin-effects and small transfer of power from the barrel.

All these waves are subject to constructive and destructive interference, so that the composite pattern builds up a traveling wave packet which changes slightly in time and space as shown in Fig. 4. The finite length of the sleeve and of the current impressed in it also give rise to a continuum of waves that induce currents in the energized coils of the barrel. The resulting drag can be estimated by using the Poynting vector (see for instance Ref. 10).

Finally, one should consider the effect of the acceleration of the wave packet over the length of the sleeve l_s. This acceleration causes the leading portion of the sleeve to slip behind the excitation wave and act as an induction motor, while the trailing portion slips ahead of the excitation wave and acts as an induction generator. The resulting pull and drag tend to balance out and therefore do not affect the thrust. Nevertheless, the acceleration effect must be assessed for reasons to be explained below.

If v_p is the velocity of the projectile, v_l and v_t are the wave velocities at the leading and trailing edge of the sleeve, and S is the slip, then from the relations

$$S_l = \frac{v_l - v_p}{v_l}\ ,\ S_t = \frac{v_t - v_p}{v_t}\ ,\ S_l = -v_t$$

one finds that

$$v_p = \frac{2v_l v_t}{v_t + v_l} \text{ and hence that } S_l = \frac{v_l - v_t}{v_l + v_t}\ . \qquad (37)$$

Introducing

$$v_l - v_t = \frac{l_s a}{(v_l + v_t)/2} \qquad (38)$$

and assuming a constant acceleration over the entire length of the barrel l_b,

$$a = \frac{v_m^2 - v_b^2}{2l_b} \qquad (39)$$

one obtains

$$S_l = -S_t = \frac{1}{4}\frac{v_m^2 - v_b^2}{\left(\frac{v_l + v_t}{2}\right)^2}\frac{l_s}{l_b} = \frac{1}{4}\frac{v_m - v_b}{v_p^2}\frac{l_s}{l_b} \qquad (40)$$

The slip is thus inversely proportional to the square of v_p the projectile velocity and near the breech is not negligible [0(.5)].

This is particularly undesirable, because the high slips result in high ohmic losses in the region of longest dwell time of the sleeve and complicate the process of impressing the system of currents on the sleeve. A solution of the problem would be to let the frequency of the current in each coil increase with time, so that the phase velocity of the wave matches that of the projectile. This, however, would add complexity to the already difficulty task of launching a few cycles of sinusoidal current in each coil.

A more desirable solution is to introduce the projectile into the barrel with a breech velocity of a few hundred meters per second as can be done, for instance, with a gas gun. In this case, calculations performed with m = 6 and n = 3 show that the losses caused by departures from the ideal conditions postulated in Sec. 3 would not prevent the achievement of the high efficiencies dictated by the thermal considerations which lead to Eq. (17).

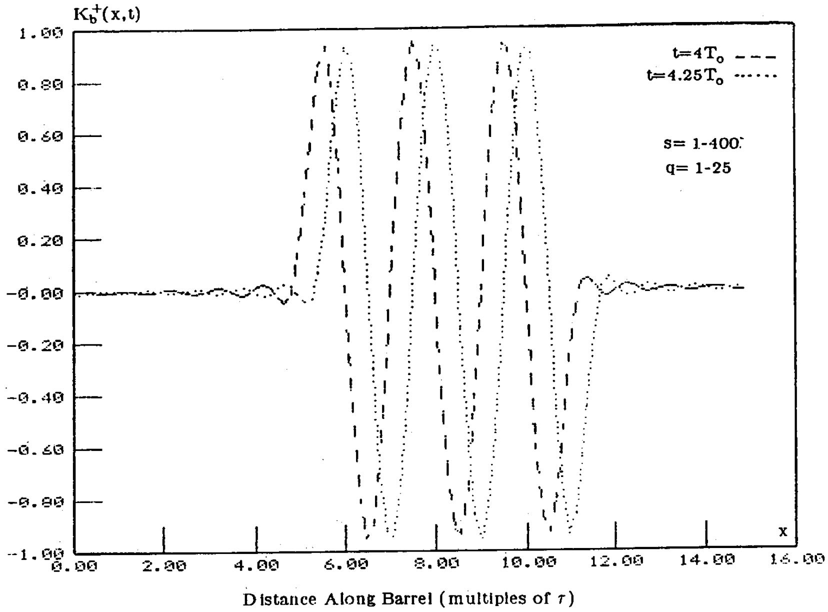

Fig. 4 Traveling wave packet on barrel.

5. Concluding Remarks

An outline of the procedure for the design of electromagnetic launchers, with particular reference to coilguns has been presented. This procedure can be adapted to the more general case in which the distributions in time and space of the currents impressed on the coils of the barrel and on the projectile sleeve are not sinusoidal. The complete design involves detailed time-dependent and three-dimensional analyses of the electromagnetic, mechanical and thermal stresses, the power conditioners, and controls needed to insure synchronization between the projectile and the wave packet, as well as longitudinal and transverse stability.

6. Acknowledgement

This work was sponsored by the SDIO/IST and managed by USASDC under contract No. DASG60-88-C-0047.

REFERENCES

1. K. McKinney and P. Mongeau, IEEE Trans. on Magnetics, Vol. 20, No. 2, March 1984, pp. 239-242.
2. M. D. Driga, W. F. Weldon, and H. H. Woodson, IEEE Trans. on Magnetics, Vol. 22, No. 6, Nov. 1986, pp. 1453-1458.
3. T. J. Burgess and M. Cowan, IEEE Trans. on Magnetics, Vol. 20, No. 2, March 1984, pp. 235-238.
4. T. J. Burgess, E. C. Cnare, W. L. Oberkampf, S. G. Beard, and M. Cowan, IEEE Trans. on Magnetics, Vol. 18, No. 1, Jan. 1982, pp. 46-59.
5. H. Kolm and P. Mongeau, IEEE Trans. on Magnetics, Vol. 20, No. 2, March 1984, pp. 227-230.
6. V. N. Bondaletov, Soviet Physics, Vol. 12, No. 2, Aug. 1967, pp. 198-202.
7. V. N. Bondaletov and E. N. Ivanov, Soviet Physics, Vol. 22, No. 2, Feb. 1977, pp. 232-234.
8. F. J. Young and W. F. Hughes, "Rail and Armature Current Distributions in Electromagnetic Launchers," IEEE Trans. on Magnetics Vol. 18, No. 1, Jan. 1982, pp. 33-41.
9. J. L. He, E. Levi, Z. Zabar, L. Birenbaum, and Y. Naot, "Analysis of Induction-Type Coilgun Performance Based on Cylindrical Current Sheet Model," 5th Symposium on Electromagnetic Launcher Technology, Destin FL, April 2-5, 1990.
10. E. Levi and M. Panzer, Electromechanical Power Conversion, McGraw-Hill, New York, 1965.