ELECTROMAGNETIC INDUCTION LAUNCHERS

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Abstract - The electromagnetic launcher consists of a system of stator coils producing a traveling field which accelerates an armature carrying currents induced by the traveling field (induction accelerator [1,2]) or persistent currents supplied from other sources (synchronous accelerator [2,10]).

The fact that their armature has no electrical contact with the stator, essentially riding on the crest of a traveling magnetic wave, makes induction accelerators very attractive for a large number of applications. This paper is devoted exclusively to the accelerator of the induction type.

Efficiency considerations require that the traveling wave should accelerate at approximately the same rate as the projectile. This can be achieved either using variable (increasing) winding pitch or a continuously increasing power supply frequency or a combination of both.

A new dimension was added to the induction coaxial accelerator technology with the definition at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) of a new electrical machine, the Rising Frequency Generator (RFG) representing a more attractive integrated power source for induction accelerators which had previously been forced to conform to constant frequency power supplies.

This paper outlines the principles of design and shows two applications of induction coaxial launchers; a half-scale aircraft launcher in which the system also acts as an electromagnetic brake, stopping the shuttle and driving it in the opposite direction, and a high performance, 18-m long launcher capable of accelerating a 1-kg aluminum projectile to a velocity of 10 km/s at an average acceleration of 250,000 G.

INTRODUCTION

The current interest in electromagnetic acceleration of masses has resulted in something of a competition between the railguns and coaxial accelerators. If proliferation is any measure of success, railguns presently appear to be leading the competition. Actually, there are several fundamental reasons why the railguns are enjoying their present surge of popularity which in no way reflects inherent superiority over the induction launchers for all applications.

Railguns are the simplest of the electromagnetic launchers and it is natural that they should be developed first. They undoubtedly benefit from the fact that virtually anyone with access to a laboratory or shop can quickly fabricate a small railgun which will accelerate a projectile. This advantage of simplicity is compounded by the scaling relationships for the two concepts. Whereas the inductance gradient of the railgun is essentially independent of scale, the comparable gradient for induction launchers is quite sensitive to it, improving dramatically in larger accelerators. Thus, it is quite difficult to build a small-scale coaxial launcher with impressive performance.

Moreover, the railgun has had the benefit of the existence of the pulsed homopolar generator in conjunction with an inductor and an opening switch, an inherently compatible power supply, that had been developed for other programs. The induction launchers enjoyed no such serendipitous benefit and have suffered as a result. In fact, much of the effort expended on the development of coaxial accelerators to date, when viewed in this light, appears to have been directed toward forcing the accelerator to conform to existing power supplies.

This paper describes efforts to solve this problem by pursuing the development of a coaxial launcher with an integrated pulsed power supply designed specifically to meet the requirements of the launcher. The potential benefits include increased efficiency, greater freedom of projectile design, and the elimination of switching and synchronization requirements.

Topological Configurations

Publications devoted to linear induction motors [1, 2, and 3], list the linear topological equivalents for all known classical electric motors, and add additional concepts. Among so many variants, few have merit as simple and efficient accelerators. We will limit ourselves to the double sided induction accelerator, (Figs. 1a and 1b), and the tubular accelerator. (Fig. 2).

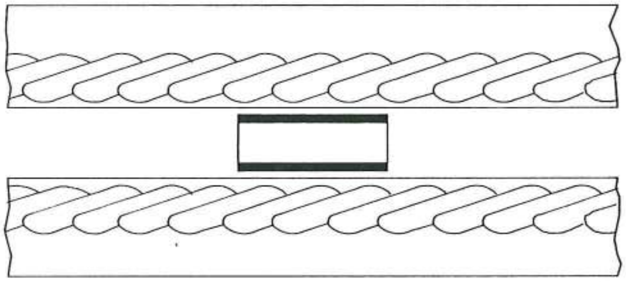

Fig. 1a. Section of an induction accelerator (long stator variant).

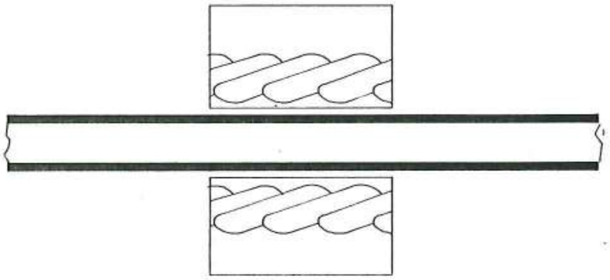

Fig. 1b. Section of a linear induction accelerator

Since in the accelerator case the moving part is a "projectile" or a "shuttle" it becomes obvious that only the "long stator" (or short rotor or shuttle) variant (Fig. 1a) is of interest*. The term coaxial implies the axial symmetry of the traveling (inductor) field and the armature induced field. Only the tubu-

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lar induction accelerator has the circular symmetry implied by the term coaxial (Fig. 2).

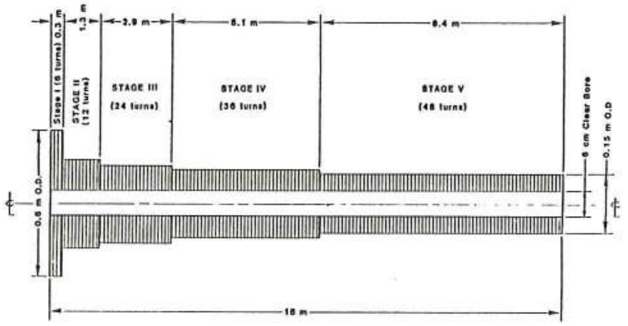

Fig. 2. Tubular induction accelerator.

Accelerated Traveling Fields

From the theory of the conventional rotating induction motors it is known that their energy efficiency for starting operation expressed in energy terms is less than 50%. For each unit of energy stored kinetically in the rotor, a greater amount is dissipated in the Joule heating of the rotor by slip losses.

In exactly the same manner[4], a projectile accelerated from rest by a constant speed traveling field will be subject to the same slip losses, which amount to W_{PJ}, for the entire launch period:

$$W_{PJ} = \int_0^t F_p s\, V_{TF}\ dt = m_p\, V_{TF} \int_0^t s\, \frac{dv}{dt}\, dt$$

Changing the integration limits

$$W_{PJ} = m_p\, V_{TF} \int_0^{V_{TF}} \left(1 - \frac{v}{V_{TF}}\right) dv$$

Where F_p = force applied to projectile (N)
m_p = projectile mass (kg)
V_{TF} = speed of traveling field (m/sec)
v = instantaneous speed of projectile (m/sec)
$s = \frac{V_{TF} - v}{V_{TF}} \times 100$ = slip (percent)

Accelerating from rest to the speed of the traveling field and neglecting friction losses gives an amount of energy loss:

$$W_{PS} = m_p V_s \left[V \frac{u^2}{2V_{TF}}\right]_0^{V_{TF}} = 1/2\ m_p\, V_{TF}^2$$

equal to the kinetic energy stored in the projectile.

Actually the projectile does not reach the speed of traveling field and the energy loss is (Fig. 3a)

$$W_{PJ} = \int_0^{Vm} m_p\, (V_{TF} - v)\, dv = m_p \left(V_{TF} \cdot Vm - \frac{Vm^2}{2}\right)$$

where Vm = projectile output velocity (at the muzzle of the launcher)

For a two stage system (Fig. 3b) comprising two traveling field speeds, the energy loss decreases considerably:

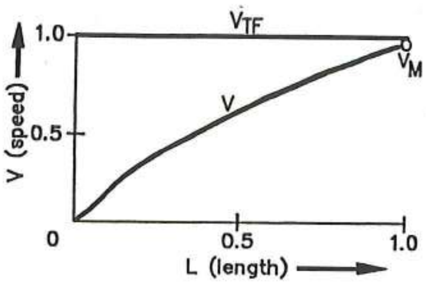

Fig. 3a. Traveling field speed and projectile speed for single-stage acceleration.

$$W_{PJ2} = \int_0^{v_i} m_p\, (V_{TF1} - v)\, dv + \int_{v_i}^{Vm} m_p\, (V_{TF2} - v)\, dv$$

If the intermediary speed $v_i = \frac{Vm}{2}$ and $V_{TF2} = 2V_{TF1}$

$$W_{PJ2} = \frac{m_p Vm}{2} \left(\frac{3}{2} V_{TF2} - Vm\right)$$

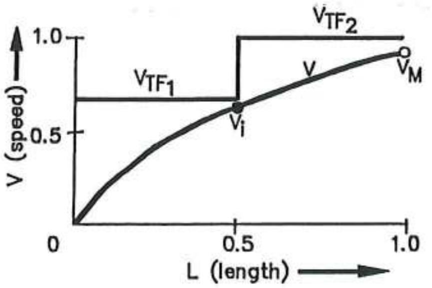

Fig. 3b. Two-stage acceleration.

The number of stages can be further increased which would considerably increase the energy efficiency and reduce to a minimum the Joule loss in the projectile. At the limit this corresponds to a continuous increase in the pole pitch or a continuous change in the frequency of the currents producing the traveling field (Fig 3c).

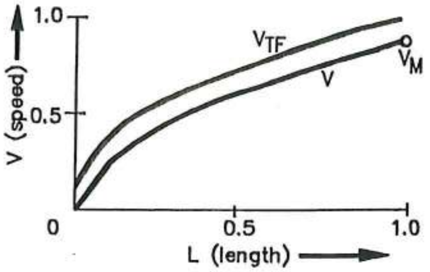

Fig. 3c. Continuously accelerating traveling field induction system.

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* However, one of the earliest applications of the short stator variant of an induction accelerator was the Westinghouse aircraft launcher, under the name "Electropult" (1946) [7].

Such system would produce an accelerating traveling field which ideally, will be followed closely by the projectile, keeping the slip (and consequently the losses) at constant, low values [3],[4].

The variable pitch winding, which sometimes is called a graded winding, is fabricated by increasing the coil spacings - thus increasing the traveling field velocity towards the end of the launcher - for the tubular construction. For a double sided variant, the pole pitch is continuously increased, also the number of turns per coil is changed progressively to obtain special effects (Figs. 2 and 4).

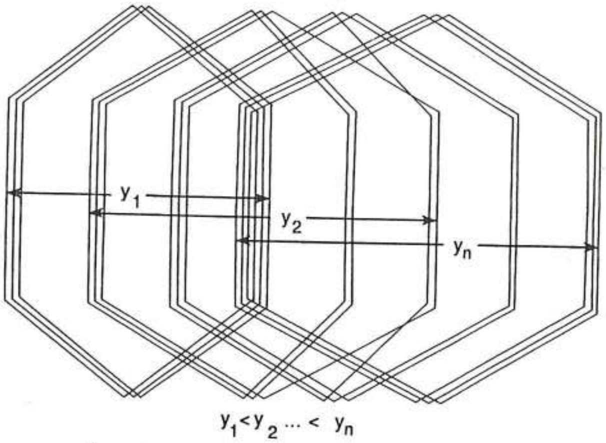

Fig. 4. Variable pitch (graded) winding.

The slots in Fig. 4 indicate spacing - since the machine is ironless in order to obtain high performance in pulsed mode.

The second manner to obtain an accelerated field is to continuously vary the supply frequency. This way, as the armature is accelerated down an essentially constant pitch stator winding, the driving frequency increases with the armature velocity. Of course, this is just the opposite of what happens in an alternator or compulsator as energy is extracted. Additionally, as the speed voltage of the accelerator rises, it is desirable for the voltage of the generator to rise as well.

A CEM concept called the "rising frequency generator" (RFG) [6] is proposed to meet the power supply requirements of the coaxial accelerator. This device can utilize the electrical generating configuration of an alternator, low impedance alternator, or compulsator -- single or multiphase. It consists of a rotor and a stator having a moment of inertia many times higher than the rotor (a naturally occurring situation which can be tailored by design) both of which are initially rotating in the same direction, the stator rotational speed being somewhat higher. The electrical frequency of the output, of course, is a function of the differential speed, $\omega_s - \omega_r$, as is the generated voltage. As power is generated, equal and opposite torques will be applied to the rotor and stator, and the rotor will change speed faster (slow down) due to its lower inertia. As the rotor slows, the differential between rotor and stator speed increases, increasing frequency and output voltage and achieving the desired effect.

A variant of this RFG concept involves using a stationary stator with a rotating magnetic field produced by a multiphase AC excitation current.

By matching the generator voltage, frequency, rotor and stator inertias, and initial velocities to the requirements of the coaxial accelerator, an integrated power supply/accelerator system can be designed. An important part of this integration is done by mounting the pulse generator excitation source (i.e., homopolar generator) on the same shaft as the pulse generator thus forming a "cascade" of electrical machines essential to obtaining the proper electromechanical energy conversion.

Analytical Treatment

Eliminating the use of iron for the magnetic circuit permits a remarkable increase in electrical machine performance, especially in those designed for pulsed power operation. (A CEM designed and built fast-discharging homopolar (1977), has shown the trade-offs and changes in a ironless high magnetic field electrical machine[5]). However, for induction accelerators this means also that the analytical tools of equivalent circuits and the theory and methodology of design related to such tool must undergo significant modifications.

The equivalent circuit (Fig. 5) represents a series connection [3] between the portion of the stator containing the projectile, where the electromechanical energy conversion takes place and the rest of the barrel which is many times longer. The first section of the equivalent circuit corresponds to the length of the projectile ℓ (neglecting all the edge effects), the second one takes into account the rest of the barrel $(L-\ell)$ where in addition to the energy loss in the stator, only reactive power is consumed.

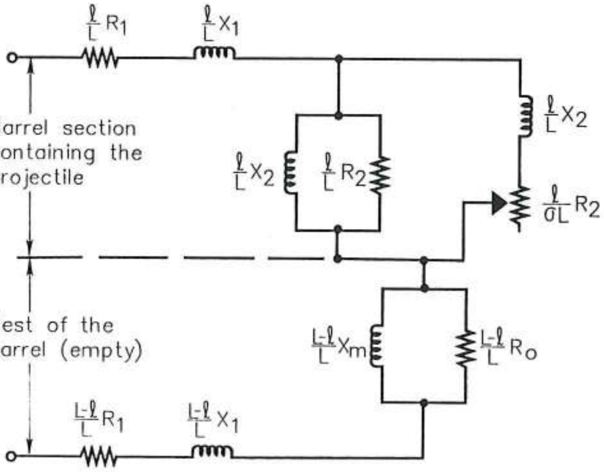

Fig. 5. Equivalent circuit of the linear induction accelerator (long stator variant).

Using a similar treatment as in classical theory of linear induction motors [3,4], in the short rotor variant, the accelerating force is

$$F = \frac{I^2 R_2 \times X_m^2}{V_s S[(R_2/S)^2 + X_m^2]}$$

optimizing the system for a maximum force loss ratio, and assuming a constant stator resistance R_1, the value of the product between the force and the speed of the traveling field, FV_s per unit stator loss results:

$$\frac{FV_s}{R_1 I_1^2} = \frac{\left(\frac{1}{L}S \frac{R_2}{R_1}\right)\left[1 + \left(\frac{X_m}{R_1}\right)^2\right]}{\left[\left(\frac{L-1}{L}\right)\left(\frac{R_2}{R_1} + S^2\right) + \left(\frac{R_2}{X_m}\right)^2 + \frac{1}{L} S^2 + \left(\frac{R_2}{X_m}\right)^2\right]\left[1 + \left(\frac{X_m}{R_1}\right)^2\right]}$$

which can be optimized even further taking R_2/X_m as variable.

In this formula, R1 and R2 are the resistances in [Ω] of the primary and respectively secondary circuits, X_m the magnetizing reactance [Ω], s is the slip and I_1 the stator current (A).

Onuki and Laithwaite [4] propose an optimization looking for the minimum stator length with the additional requirement of a permissible heat loss based on Euler-Lagrange's equations

$$\frac{\partial}{\partial v_s}\left[\frac{m_p V}{2 \cdot FR_2 \left(\frac{1}{x_1} + \frac{1}{x_m}\right) V_s \frac{(v_s - v)}{(v_s - v)^2 + \left[R_2\left(\frac{1}{x_1} + \frac{1}{x_m}\right)V_{TF}\right]^2}}\right]$$

$$+ \lambda \frac{\partial m_p (v_s - v)}{\partial v_s} = o$$

where λ are the Lagrange multipliers, imposing the constraints mentioned above.

However, efficiency considerations exclude the use of the induction accelerator with uniform properties per unit length of stator. A continuous varying pitch, a continuously increasing supply frequency during the launch or a combination of both makes the equivalent circuit lose its meaning as a tool for easy modeling of the machine properties. For computer-based design such a concept is however useful. A time marching procedure, continuously changes the parameters of the equivalent circuit, as the projectile advances through the barrel.

An iterative procedure takes into account the influence of the transient processes produced by switching-on the symmetric system of voltages to the accelerator, and also the influence of parameter variations, (supply frequency, reactances, polar pitch, resistance increase due to field diffusion, temperature rise) [8,9].

The design for the two following examples of induction accelerators was done segment by segment (for the stator winding) using a finite element electromagnetic code described elsewhere [6]. The speed of the projectile at any instant, and at any point along the barrel is a function of the j x B forces and the speed history since the beginning of the launch, such that a recursive procedure is used for each segment of the machine, in a "space" marching algorithm.

Shown in Fig. 6 is the flux plot of the accelerated traveling field in which the frequency of the power supply is continuously increasing, sweeping equal polar pitches in decreasing amounts of time. In Fig. 7, the same effect is obtained by a continuously increasing pole-pitch.

The space marching algorithm with its recursive nature and the corrections for transient phenomena apply similarly to both cases (Figs. 6 and 7).

For the projectile design a two-dimensional finite element diffusion code was used. The original TEXMAP transient electromagnetic finite element code

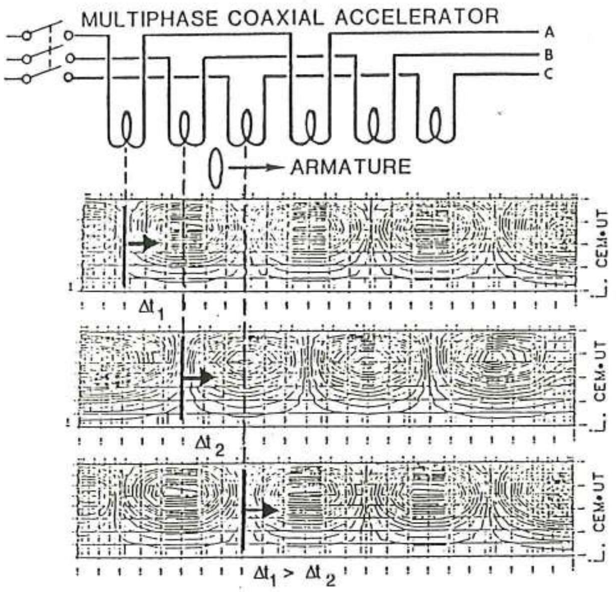

Fig. 6. Flux plot of an accelerated traveling field: $\Delta t_2 < \Delta t_1$ (increasing frequency).

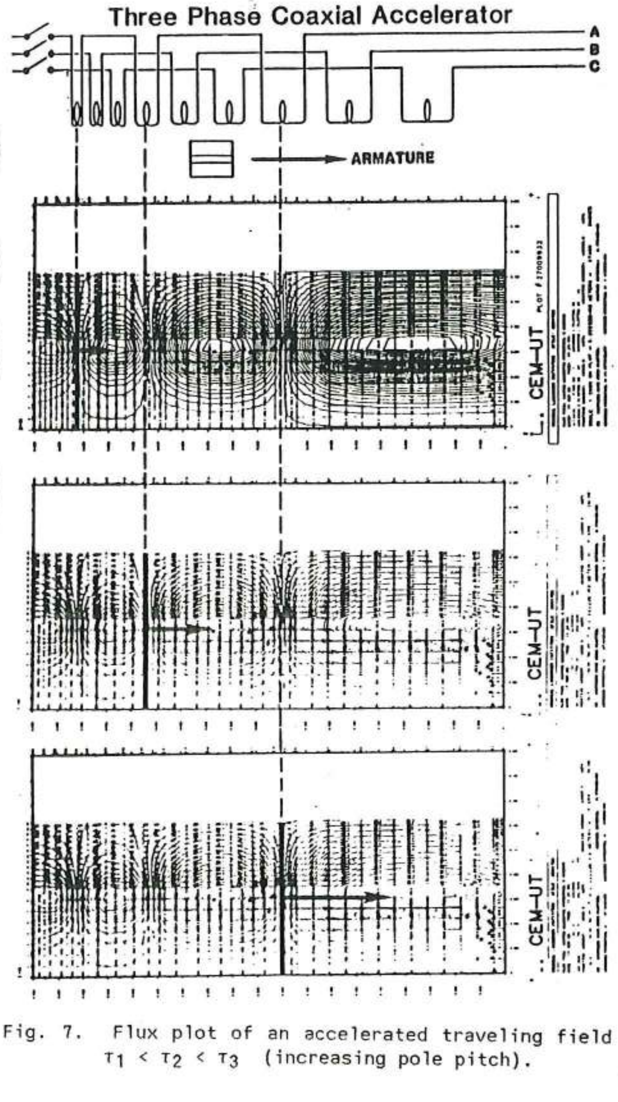

Fig. 7. Flux plot of an accelerated traveling field $\tau_1 < \tau_2 < \tau_3$ (increasing pole pitch).

has been modified in order to apply to the coaxial accelerator problem. As was reported in a previous paper [5], the formulation of such code is in terms of two potentials: vector A and scalar ψ, subject to the condition div A = 0 imposed by Lagrange multipliers. The Galerkin formulation was used for the solution of Maxwell's equations in a moving medium. The edge effects were approximated and added to the final results. In a short time CEM-UT will have an operational 3D transient electromagnetic code, capable of exact calculations of the edge effects in the most general conditions.

Two examples of conceptual design of induction launchers:

The first example is a proposal for a coaxial induction accelerator having the task of accelerating a 1-kg projectile to a velocity of 10 km/s. The purpose of such a conceptual design is to establish size and performance levels and is likely that it will undergo substantial evolution.

The conceptual accelerator is 18-m long and will accelerate a 1-kg aluminum projectile to a velocity of 10 km/s in 3.6 ms at an average acceleration of 250,000 G. Although it is anticipated that the stator coil pitch and aspect ratio will vary continuously in the final design, five discrete stages of differing pitch and aspect ratio are considered in this conceptual design (figs. 2 and 6). The windings are of constant cross-sectional area and the winding spacing (pitch) changes from stage to stage. The peak terminal voltage of the accelerator with all stages connected in series is 28 kV. The peak center line flux density is 15.5 T (11 T rms) which reflects a peak field of 20.6 T at the surface of the stator conductors. Although this flux density is quite high, it is within the state of the art for reinforced solenoids, such magnets having been operated steady state up to 30 T center line field and in the pulsed mode at fields far above that level.

The projectile is a 1-kg aluminum cylinder approximately 0.06 m in diameter and 0.15 m long. The projectile will be magnetically centered in the accelerator and will nominally not contact the stator although some guide rails will be provided to protect the stator coils in the event of a malfunction. Current will be induced in the aluminum projectile due to slip. A difference between projectile velocity and the velocity of the traveling magnetic wave is produced by the stator coils. In modeling done to date, average slips between 0.65 and 0.95% have been considered resulting in armature temperature rises during launch between 479 and 694°C. It is probable that liquid nitrogen precooling would be used in either case for improved efficiency and to provide a more attractive thermal operating margin. It is anticipated that more aggressive cooling techniques such as transpiration cooling will be investigated during the design phase.

The rising frequency generator (RFG) will be designed specifically to power the passive coaxial accelerator. A generator frequency ratio (final frequency/initial frequency) of approximately four is required in the design presented here. This suggests that initially the generator rotor would be spinning at 90% of stator speed extracting about two thirds of the energy stored in the rotor. The stator which also rotates in the RFG would store substantially more energy than the rotor, but would be essentially unaffected by the discharge. The estimated system efficiency for the conceptual design is 28%.

A second example (Figs. 7 & 8) refer to a design of a prototype, subscale, electromagnetic aircraft launcher (Nimitz-class). Such a launcher (catapult) is built as an induction accelerator having a more conservative design, than the accelerator presented in the first example. The passive, iron-free modular launcher has an increasing pitch, three-phase stator winding.

The active part of the stator is 12 ft (3.66 m) long and in designed to achieve a continuous 5 g acceleration of an 18,000 lb (8,182 kg) load. A three-foot section is included at the end of the stator for counter current braking of the shuttle alone at a higher level of deceleration.

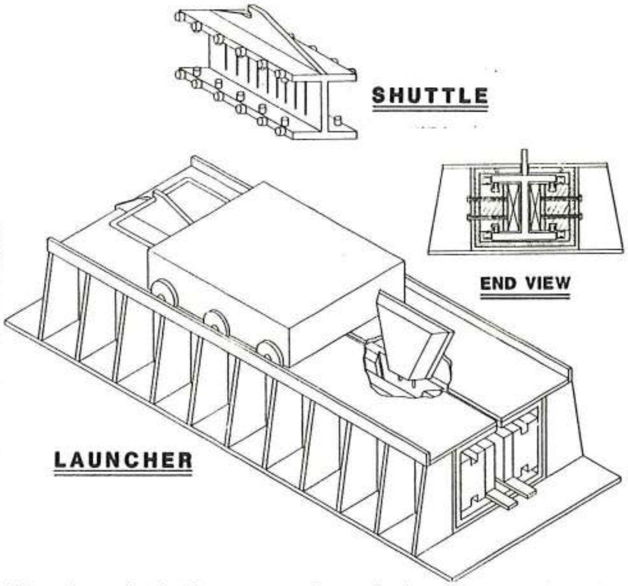

Fig. 8. Artist's conception of the electromagnetic aircraft launcher.

CEM-UT analysis of the point design for the 12-foot launcher has shown that the slip losses in the armature will increase only slightly (from 4.25% to 4.6%) if the stator pole pitch is increased in three discrete steps rather than varying continuously. In order to minimize the cost and complexity of the proposed scale-model launcher through modularization, CEM-UT has chosen to build the prototype with three discrete stator-coil spacings representing synchronous speeds of 6.6, 13.2 and 19.2 m/sec.

Braking is achieved by simply reversing the connection of two stator phases to the power line, essentially causing the traveling magnetic wave to reverse direction. Shuttle return is accomplished by operating the accelerator and braking coils in reverse at reduced power.

Although the proposed, scale-model electromechanical catapult will be operated directly from the utility grid, it is anticipated that the full scale accelerator would be powered by dedicated alternators driven by auxiliary turbines. Such alternators could include inertial energy storage to average peak launch power over the total, launch-cycle time, thereby reducing peak demand on the prime-power system. Low impedance alternators of the compulsator design, pioneered at CEM-UT, would be particularly suitable for such duty. The Rising Frequency Generator (RFG), would be capable of producing and delivering an increasing- frequency, AC pulse to a full scale accelerator. This would allow the launcher to be built with constant-pitch, stator-coil spacing which would provide an increase in launcher efficiency.

The stator-coil modules will be fabricated for easy replacement in the event of damage or insulation failure. They will be built using standard NEMA class F, epoxy-mica paper based insulation developed for 12.8 kV industrial motors. Passages for forced-air cooling will be provided to keep the stator coil temperature well below 155°C operating limit for class F insulation. The coil modules will slide into dovetail slots in the stator-support structure, completing electrical and cooling connections as they fit into place. The stator-support structure will also be modular (tentatively planned as 3-ft sections) to enable alteration of length at will.

The winding density (number of turns per coil module) will vary in different modules in order to obtain constant acceleration as shuttle speed increases.

The shuttle is essentially a fabricated I-beam section of 6061-T6 aluminum with both sides of the central web clad with 6-mm thick brass plates. Although the shuttle will be magnetically centered between the stator coils and will nominally not contact the stator, a guidance system of high-speed guide rollers and tracks is provided to react against the offset pull of the deadload and ensure that the armature does not damage the stator coils.

The use of two materials of substantially different conductivity in the armature web produces the maximum driving force under all operating conditions with minimum consumption of reactive power. When the shuttle is being decelerated, the frequency of the induced current rises to almost 120 Hz, the depth of penetration into the web is reduced, and the armature current flows in the resistive brass cladding aiding in the braking process and delivering a favorable power factor. The 6-mm wide vertical slots in the shuttle web are placed to control the eddy current pattern in the armature.

A three-phase, vacuum, circuit breaker is used to connect and disconnect the stator windings to the 15-kV power line. The average power per acceleration cycle for the 12-ft accelerator is 12.62 MW. The power factor for this system is low so that the apparent power required is 21.04 MVA. The electrical substation installed at the new CEM-UT laboratory is capable of providing the required power.

The total energy delivered to the accelerator during the launch is 4.87 MJ for a cycle efficiency slightly above 30%. The reactive power however has relatively high values.

CONCLUSIONS

The induction coaxial accelerators in ironless, high magnetic field construction with integrated power supply have high potential benefits. Such benefits include, elimination of switching and synchronization requirements, greater freedom of projectile design, and increased efficiency. However the methods of modeling and calculating classical induction motors (rotational and linear) are not applicable and the use of two and three dimensional transient, finite element electromagnetic codes coupled with thermal and stress finite element computer codes are essential in obtaining high performance launchers. Rigorous three dimensional modeling of the edge effects, especially on the projectile, is very important in achieving high performance indices.

ACKNOWLEDGMENTS

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