TRAVELING-WAVE SYNCHRONOUS COIL GUN

David G. Elliott
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Abstract

A traveling-wave synchronous coil gun permits independent adjustment of the magnetic field and armature current for high velocity at low armature mass fraction. Magnetic field energy is transferred from the rear of the wave to the front without passing through the power supply. Elaborate switching is required.

Gun Concept

The traveling-wave synchronous coil gun is an extension of the brush-commutated coil gun concept [1]. In that concept a pair of brush-fed armatures is propelled by the radial magnetic field at the leading and trailing edges of a traveling wave of barrel current. The rise of barrel current at the leading edge of the wave is induced by the magnetic field of the front armature, and the fall of barrel current at the trailing edge is induced by the field of the rear armature.

The traveling-wave synchronous coil gun uses the same geometry as the brush-commutated coil gun, but the rise and fall of barrel current is produced by external voltages, permitting a higher magnetic field for a given armature current. The geometry is shown in Figure 1. The barrel coils are connected in series, forming a single helical coil. Current enters the barrel coils near the center of one armature and leaves near the center of the other. The multi-turn armatures are fed from rails through brushes. The radial magnetic field at each end of the barrel excitation region pushes on the armature currents, which flow in opposite directions in the two armatures.

Excitation

A high voltage is applied to the coil opposite the front armature to bring the current up from zero, and a negative voltage is applied to the coil opposite the rear armature to return the current to zero. The beginning and ending conditions for a wave shift of one coil pitch are illustrated in Figure 2 for an accelerator with seven coils in the excitation length. Initially there is full current (designated as unity) in coils 1 through 6 and zero current elsewhere. Coil 7 rises to full current and coil 1 drops to zero as the barrel current wave and armatures move one coil pitch.

The barrel current is supplied by two power supplies that operate at different voltage levels, high (H) and low (L). During the wave shift the H supply rises to full current and the L supply falls to zero. As will be seen, this arrangement allows the magnetic field energy at the rear of the wave to be transferred to the front of the wave without energy being transferred through the power supplies.

In the absence of an armature (Figure 3a), supply L receives power from coil 1 as the field at the rear of the wave decays, and supply H furnishes power to coil 7 as the field at the front rises. However, much of the magnetic field energy at the rear of the wave is linked with the rear interior coils 2 and 3, and that energy flows directly to the front interior coils 5 and 6 because the voltage rise in coils 2 and 3 matches the voltage drop in coils 5 and 6.

When a projectile is being accelerated (Figure 3b) the L supply operates at positive voltage and is an energy source; the energy returned from coil 1 reduces the output required from supply

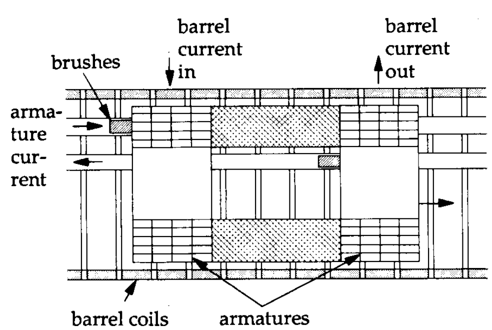


Figure 1. Traveling-wave synchronous coil gun

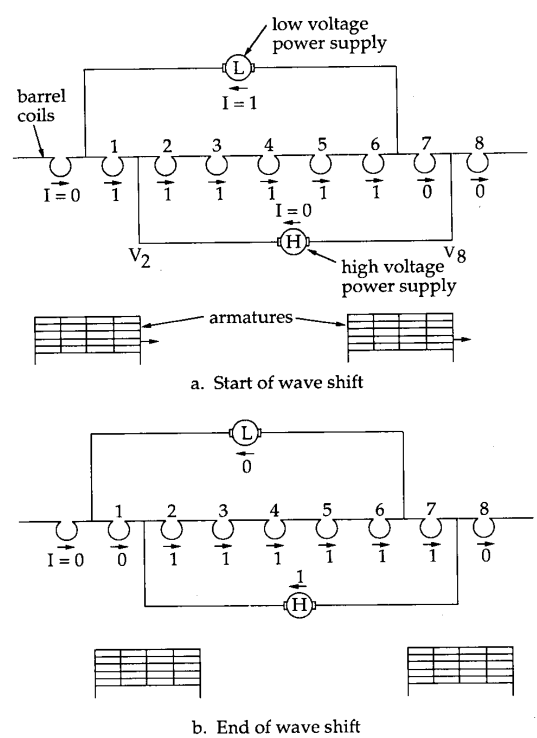
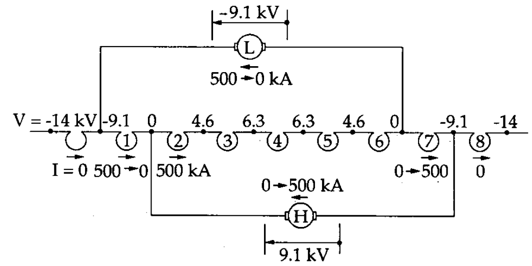
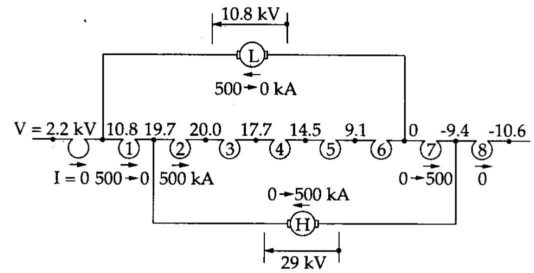


Figure 2. Excitation method

0018-9464/91/0100-0647$01.00 © 1991 IEEE



a. With no armature and no coil resistance



b. With armatures and coil resistance

Figure 3. Typical barrel currents and voltages

L but does not require L to receive energy. As a result, the energy furnished by the two power supplies during launch is just equal to the sum of the projectile kinetic energy and the barrel and armature ohmic losses.

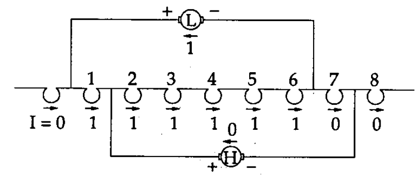
Switching

The switching sequence for the power supply connections is shown in Figure 4. In the first two steps (a and b) the current in coil 7 rises to full value and the current in coil 1 drops to zero. The current in the L supply is then zero and L is disconnected. In the next step (c) the H supply is replaced with the L supply. During the exchange the current in H drops to zero and the current in L rises to full value. The H supply is then reconnected a coil pitch further down the barrel (step d).

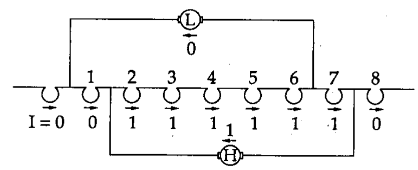
Brush Commutation

Figure 5 shows how the switching could be done using brush commutation. The "brushes" are traveling arcs or triggering devices that make and break pairs of contacts in the barrel. There are four brushes on the armatures. Inside the barrel there are two rows of contacts connected to the barrel coils and four rows of contacts connected to the power supplies, each row with alternating H and L contacts.

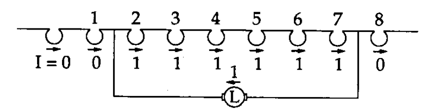
In Figure 5a, which corresponds to Figure 4a, the upper brushes connect the positive side of L to the left side of coil 1 and the negative side of L to the left side of coil 7. The lower brushes connect the positive side of H to the right side of coil 1 and the negative side of H to the right side of coil 7. Between step (a) and step (b) the brushes slide to the right, the current in coil 7 rises to full value, and the current in coil 1 falls to zero. In step (c) the upper brushes are disconnected from the barrel coils and the lower brushes are switched to supply L.



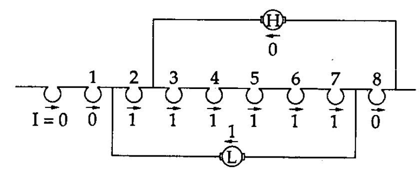
a. Start of shift



b. End of shift



c. Disconnect L, replace H with L



d. Connect H one coil further along

Figure 4. Power supply switching sequence

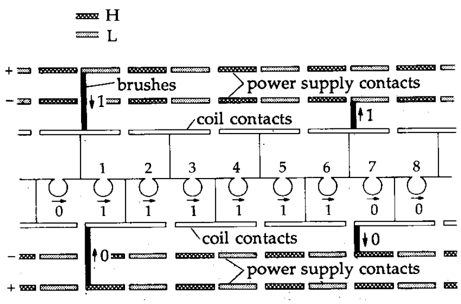
In step (d) the lower brushes connect the positive side of L to the left side of coil 2 and the negative side of L to the left side of coil 8. The upper brushes connect the positive side of H to the right side of coil 2 and the negative side of H to the right side of coil 8. The wave has moved one coil pitch and the cycle can start over.

Power Supply

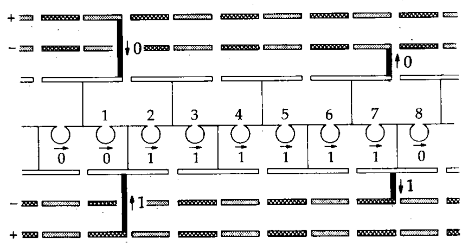
The power supply arrangement is shown in Figure 6. A dc generator such as a compulsator feeds constant current. A capacitor across the line provides storage for the energy pulses delivered at each wave shift. The energy delivered per pulse is equal to the launch energy divided by the number of barrel coils, which is 500 or more. If the voltage is allowed to vary by 5 percent then the capacitor needs to have an energy storage capacity equal to only 20 pulses, or 4 percent of the total energy requirement.

Performance

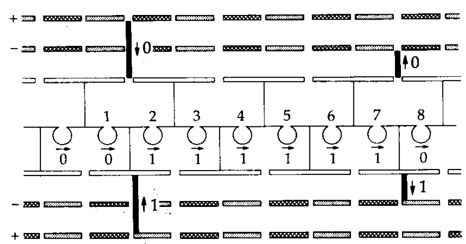
High velocities are possible at low armature mass fractions. Two examples are given in Table 1. A 7.5 kg launch mass can be accelerated to 5 km/s by a 1.5 kg armature (0.75 kg of aluminum and 0.75 kg of insulation and reinforcement) in a 100 mm diameter barrel. A 30 kg launch mass can be accelerated to 20 km/s by a 12 kg armature in a 200 mm diameter barrel.



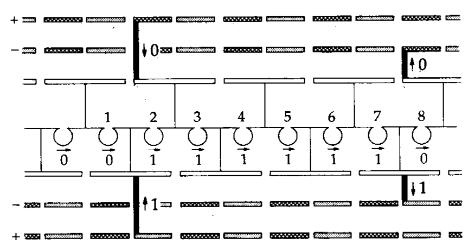
a. Start of shift (L connected on top, H on bottom)



b. End of shift



c. Disconnect L (top), replace with L (bottom)



d. Connect H (top) one coil further along

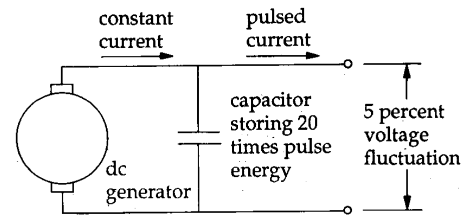
Figure 5. Switching with brushes

Acknowledgements

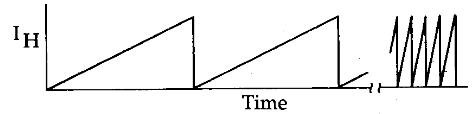
The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Army Armament Research, Development and Engineering Center.

References

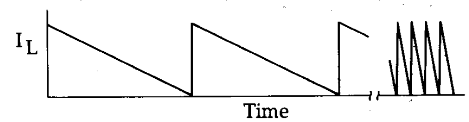
[1] W. R. Snow and H. Kolm, *Electromagnetic Acceleration Task 8*, Final Report, Electromagnetic Launch Research, Inc., Hudson, Mass., March, 1989.



a. H and L power supplies



b. H current waveform at start and end of launch



c. L current waveform at start and end of launch

Figure 6. Power supply and waveforms

Table 1. Synchronous launcher examples

Performance parameter	Low speed	High speed
Muzzle velocity, km/s	5.0	20
Projectile mass, kg	4.0	14
Projectile kinetic energy, MJ	50	2800
Projectile diameter, mm	25	100
Barrel bore diameter, mm	100	200
Barrel length, m	14	200
Number of barrel coils	700	5000
Armature mass, kg(1)	1.5	12
Sabot mass, kg	2.0	4
Launch mass, kg	7.5	30
Launch kinetic energy, MJ	94	6000
Number of series turns per coil	2	1
Barrel coil current, kA	640	2700
Armature current, kA(2)	32	68
Magnetic field, T(3)	12	13
Armature voltage, kV	1.4	1.6
Final barrel voltage (supply H), kV	75	320
Barrel ohmic loss, MJ	2.8	23
Armature ohmic loss, MJ	0.3	2
Electric input energy MJ(4)	107	6630
Launch KE/Electric input, percent	88	90
Projectile KE/Electric input, percent	47	42

(1) Half aluminum and half reinforcement, aluminum heated from 25 °C to 370 °C (action integral = $2x10^{16}$)

(2) With 40 series turns per armature

(3) Radial field component at the center of the armatures

(4) Launch kinetic energy plus ohmic losses plus 10 percent