THE CONCEPTUAL DESIGN OF A LIGHTWEIGHT COMPULSATOR-DRIVEN ELECTROMAGNETIC ACCELERATOR

Prepared by

M.L. Spann, S.B. Pratap, W.A. Walls, J.D. Herbst

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Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
Bldg. 133, EME 1.100
Austin, TX 78758
512/471-4496

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M. L. Spann, S. B. Pratap, W. A. Walls and J. D. Herbst

Center for Electromechanics
The University of Texas at Austin
Austin, TX 78758-4497

Summary

The development of light-weight pulsed power supplies which can deliver significant amounts of energy in a properly conditioned pulse has been an issue throughout the investigation of electromagnetic (EM) launchers and other areas of high-power physics research. Compensated pulsed alternators (compulsators) are low impedance alternators which are capable of producing currents in the MA range. In recent years it has become apparent that the compulsator is well suited for driving EM guns. The generators have the high energy density inherent in rotating machines, can supply repetitive pulses, and eliminate the need for the high-current opening switch required in homopolar generator driven systems. Ultimately, compulsator-driven EM gun systems may replace conventional chemical weapons. This paper describes the first attempt to design and fabricate a self-contained, compulsator-driven, portable EM gun system.

Introduction

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) is currently involved in an ambitious and exciting program which will advance the state-of-the-art in electromagnetic accelerators and lightweight, high power pulsed power supplies. The project, funded through the U.S. Army Armament, Research, Development and engineering Command (DAAA21-86-C-0281), supports the Electromagnetic Gun Weapon System program (EMGWS). The EMGWS program goal is to produce a new armored vehicle utilizing an electromagnetic gun. The program has been divided into four tasks:

A-- to design, fabricate, and test a full-scale armored vehicle which incorporates an electromagnetically driven gun to accelerate projectiles to a muzzle energy of 15 MJ,

B-- to build a sub-scale, single-shot, laboratory based accelerator to operate at the 9 MJ projectile energy level using conventional power supplies,

C-- to build a portable, stand-alone, rapid-fire accelerator and power supply to operate at the 9 MJ level,

D-- to fabricate projectiles for the above systems which are compatible with the environment of an EM gun and demonstrate superior armor penetration and ballistic characteristics.

This paper reports the efforts of CEM-UT in the area of Task C, and is a summary of the conceptual design and component testing done to date.

The 9 MJ, rapid-fire system will require considerable advancement in the state-of-the-art of critical components including the pulsed power supply, EM accelerators, thermal management and auxiliary systems. The goals of the 33 month program are to design, fabricate, and test under field conditions a stand-alone EM gun system including integrated prime power, power conditioning, supporting auxiliaries, autoloader, and gun. The EM gun is to be capable of accelerating projectiles to a muzzle energy of 9 MJ at muzzle velocities in the 2.5 to 4 km/s range. It is designed to fire a burst of three shots per minute for a period of three minutes. A weight limit of 20,000 kg has been imposed, and the system should be of a volume consistent with armored vehicle capabilities.

The CEM-UT system will use a compensated pulsed alternator (compulsator) as the pulsed power supply. The compulsator is basically a single phase, low impedance alternator which operates at extremely high power levels (in terms of rotating machines), and is capable of producing a variety of pulse shapes. The compulsator is applicable to portable, rapid-fire EM gun systems since it can perform single element energy storage, power generation and conditioning, and inherently produces a series of pulses. Due to the alternating nature of the voltage generated, there is a naturally occuring current zero at which time the pulse may be interrupted as the projectile exits the gun. This eliminates the destructive muzzle flash in the gun and implies that the system can be operated at high efficiencies since there is no stored magnetic energy in the discharge circuit at the end of the pulse.

The EM gun system is shown schematically in Figure 1. It is composed of four major subsystems; the auxiliaries, prime power, pulsed power, and the EM accelerator.

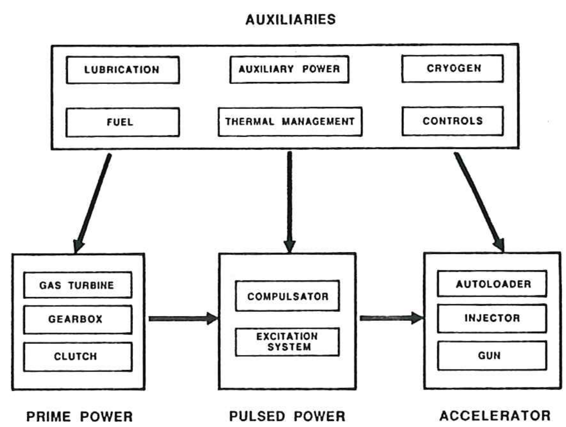

Figure 1. System component schematic

Prime Power/Drive System

The prime mover for the Task-C project will supply the energy requirements for the EM launcher as well as the various auxiliaries of the unit. Due to the stringent size and weight limits of the contract, the only feasible choice is a gas turbine. In order to reduce the overall risks of the program, it is desirable for the turbine to be a proven, reliable power source which will perform with a minimum of maintenance. Initial tests will be held at an unspecified government test range. Therefore, the engine must be capable of supplying the required horsepower at an elevation of 1,200 m and an ambient temperature of 43°C. The loads on the prime-power system can be divided into two classes: 1) replacing the inertial energy in the rotor to provide field excitation and drive the launcher and, 2) the power required by the various auxiliary systems of the unit. The estimated load profile is shown in figure 2.

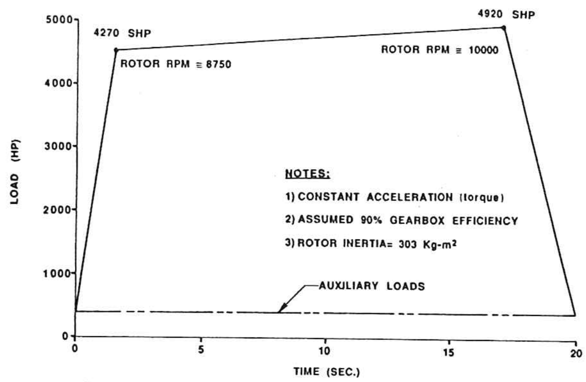

Figure 2. Prime power load cycle schematic

The energy required to provide field excitation will be supplied from the inertial energy stored in the spinning rotor, and will consist of approximately 10 MJ of stored magnetic energy plus an additional 4 MJ of resistive losses in the field-coil circuit. In addition, the railgun will require approximately 23 MJ of inertial energy out of the rotor to provide the 9 MJ of kinetic energy in the projectile. The turbine will also have to provide enough power to compensate for the frictional losses in the gearbox and compulsator hydrostatic bearings. These loads will slow the rotor from the normal operating speed of 10,000 rpm to 8,750 rpm during a typical discharge sequence. A General Electric LM500 turbine, rated at 4000 KW while weighing only 580 kg, has been selected for use as the prime mover. The GE LM500 operates at an output shaft speed of 7000 rpm. The compulsator will operate at 10,000 rpm while auxiliary pumps require power in the 1200 to 3600 rpm range. This dictates the use of a speed increasing gearbox with several lower speed power take-offs.

During the period when the excitation field is building and the discharge occurs, kinetic energy is being extracted from the compulsator rotor at a rate far exceeding the capability of the gas turbine to supply. This causes the rotor to decelerate very rapidly, at a rate which would damage the gearbox and turbine. Therefore, a clutch is required to limit the torque seen by these components. Several concepts were considered, including overrunning clutches, fluid couplings, and slip clutches. Due to reduced weight and complexity a slip clutch has been chosen for development.

Pulsed Power System

The pulsed power system converts the steady-state shaft power of the prime power system into a series of discrete high-power electrical pulses. This is accomplished by the use of an air-core compulsator and a self excitation system. The compulsator concept was conceived at (CEM-UT) and patented in 1978. [1] Since that time, CEM-UT has fabricated and tested several machines which have successfully proved the theory of operation, and have led to a thorough understanding of the machines.[2,3] Most recently, CEM-UT has fabricated a compulsator specifically for use in an EM gun system. The machine, designed to accelerate 80 g projectiles to 2 km/s in a 60 hz rate of fire, is currently in the final stages of the testing program. [4]

Unfortunately, the previous experience cited has relied upon the use of ferromagnetic materials to enhance the production of excitation flux and as an energy storage medium. The weight limitation imposed on the Task C project preclude the use of this technology. Air-core machines are ones in which ferromagnetic material is replaced by lightweight composites. The composites are very strong and stiff, and are therefore a good choice for an energy storage flywheel material. The difficulty with the concept lies in the production and control of the required excitation flux. The volume occupied by the magnetic flux is very large, and leads to two major loss mechanisms; joule losses (I^2R) in the coil itself, and the magnetic energy stored in the field (which cannot be economically recovered). Therefore, the field coil tends to be the critical or driving component in the design of these machines. Three types of field coils were considered; "room temperature" coils which would be water or freon cooled, liquid nitrogen cooled cryogenic coils, and superconducting coils. Room temperature coils were unfeasible due to their large mass and high losses. Superconducting coils, while attractive from a performance point of view, require complicated thermal insulation, and auxiliary support systems. Also, it was felt that the superconducting coil is not sufficiently stable or rugged to operate in the field environment. Therefore, a liquid nitrogen cooled coil is a reasonable compromise between these extremes.

A cross-sections view of the Task C compulsator is shown in figure 3, and machine parameters are listed in Table 1. The machine consists of a Kevlar/epoxy composite flywheel which supports the two pole, three turn-per-pole armature winding. A graphite overwrap constrains the armature winding against centrifugal forces. The armature is passively compensated through the use of an electrically conductive shield located on the bore of the stator. The shield must sustain large discharge forces which are a result of the interaction of the compensating currents and the magnetic fields produced by the armature winding. The forces result in a torque and an outwardly directed radial pressure. A 7050 aluminum alloy has been selected as the shield material. At this time, it is envisioned that the shield will be supported radially by a graphite overwrap, and that the discharge torque will be transmitted through the overwrap to a series of metallic plates. The plates will be attached to the stator casing which is rigidly tied to ground through the stator endplates. Aluminum conductors wound in two "pancake" coil configurations will provide the excitation flux.

Table 1. TASK C compulsator parameters

Stored Energy	150 MJ
Tip speed	670 m/s
# poles	2
# turns per pole	3
Open circuit Voltage	6.2 kV
Peak current	4.5 MA
Peak Power	27 GW
Pulse width	4.4 mS
Mass	8200 Kg

A problem unique to the air-core concept has been encountered. Since the excitation flux path cannot be controlled through the use of fesromagnetic material, eddy current losses, particularly in the rotor shaft area, become significant. This problem is aggravated by the high tip speed at which the machine operates. A metallic shaft is desirable from a fabrication and dynamics standpoint, however the losses in the material due to its relatively high conductivity are prohibitive. Therefore a composite shaft is required.

Graphite, which has the highest modulus to density ratio, is the structural composite of choice. Unfortunately, tests have indicated that even the relatively low transverse conductivity of the composite leads to unacceptable losses. This problem was addressed in the armature overwrap by circumferentially slitting the wrap to form axial laminations. This concept will limit the form current losses in the overwrap to an acceptable level, but is not feasible for the shaft since it must transmit torque and have high bending stiffness. Boron composites were considered but the material is very difficult to fabricate and is extremely expensive. A shaft design utilizing graphite mixed with Kevlar fibers to lower the transverse conductivity is currently being investigated.

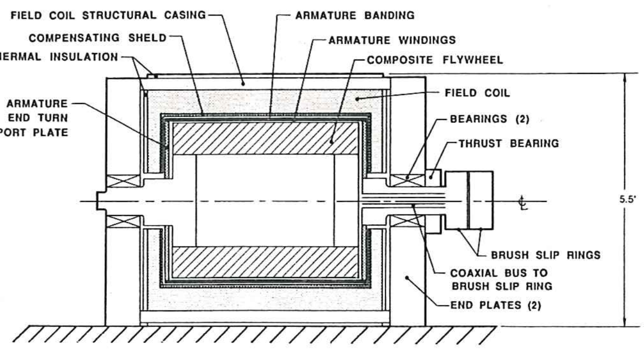

Figure 3. Compulsator cross-section

EM Accelerator

The EM accelerator consists of three components; the autoloader, the injector, and the EM gun.

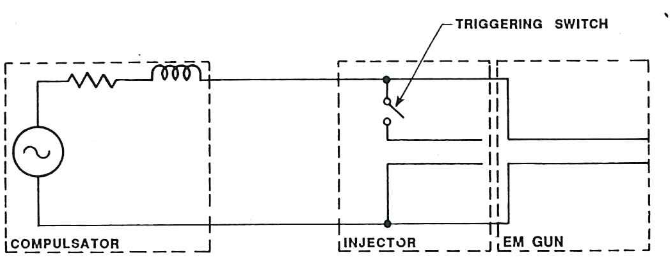

Figure 4. Electrical circuit schematic of the 9-MJ EM gun system

Autoloader

The autoloader performs the same function as an autoloader in any conventional rapid-fire gun. It must hold a clip of projectiles, and automatically index a new projectile into the breech of the injector at the appropriate time. Since the gun does not operate from a chemically produced pressure, as in a conventional gun, the breech may be left open during the discharge. Little design work on the autoloader has been done to date, however it is currently envisioned to be a hydraulically driven, nine cradle system rigidly mounted to the breech of the injector. With the relatively slow rate of fire very little difficulty is anticipated in the autoloader system.

Injector

The pulse width and peak current from a compulsator are dependent on the phase angle at which the pulse is initiated. In order to minimize arc damage and extract peck performance from the accelerator, the pulse initiation must be timed with an accuracy of ± 100 μs.

Mechanical switches have a jitter typically in the range of milliseconds and therefore cannot be used to initiate the current pulse. Electrically actuated switches have a adequate actuation time, but do not have very high current carrying capabilities. The "hot rail" concept shown schematically in fig. 4, has evolved as a solution to these problems. In this scheme the main acceleration rails are directly connected, without a switch, to the terminals of the compulsator. The armature of the projectile itself then acts as a closing switch for the railgun circuit. The projectile is accelerated to about 200 m/s by an augmented electromagnetic injector with a prepulse from the compulsator. The current in the injector is initiated at the proper phase angle by an electrically actuated switch. The advantage of this scheme is that the current in the injector is much lower than that in the main rails, greatly reducing the duty of the triggering switch.

In order to determine the accuracy and repeatability of the injector, CEM-UT has designed, built, and tested an augmented electromagnetic injector. The tests on this device indicated an accuracy in timing to within ± 60 μs.

The closing switch remains one of the difficulties associated with this concept. At this time a workable switch which meets all the desired requirements has not been identified. Options which will be considered include; a triggered vacuum spark gap, silicon controlled rectifiers (SCRs), and ignitrons.

EM Gun

The development of a lightweight, reusable railgun assembly is a challenging aspect of the Task C program. One of the primary considerations in the design of a railgun has to do with the stiffness of the rail support structure. Small rail-to-rail deflections due to magnetic loading have extremely adverse effects on gun performance. Typically, a rail-to-rail deflection will result in an inward movement on the sidewall insulators which, at lower speeds, can interfere with the projectile flight. Also, in plasma armature guns, small deflections will allow the plasma to escape by the projectile. This diverts current from the armature, and leads to lower system efficiency. Rail and sidewall erosion is also a problem. High-performance guns generally require honing, or in some cases a complete rebuild, between shots. These considerations have led to the development of steel railgun structures. Which are typically bolted together to allow disassembly and refurbishing. Due to the multi-shot requirement, and weight limitations, the Task C railgun design must follow a different tack.

The conceptual design of the railgun is shown in figure 5. Much of the detail design of the gun has been postponed until the later stages of the project to fully utilize the advances being made in railgun technology. The gun will have a 90 mm round bore, and be 7 m in length. Oxygen-free copper, or molybedenum are the candidates for the rail material. Rail containment and stiffness will be provided by a series of tubes formed of lightweight, high-stiffness composite material such as graphite, glass, boron reinforced epoxy. A major portion of the containment structure would be composed of hoop-wound material in order to obtain a high radial strength and stiffness, however several layers of off-axis wound fibers are also required. The off-axis fibers provide sufficient axial stiffness to limit longitudinal bending of the gun.

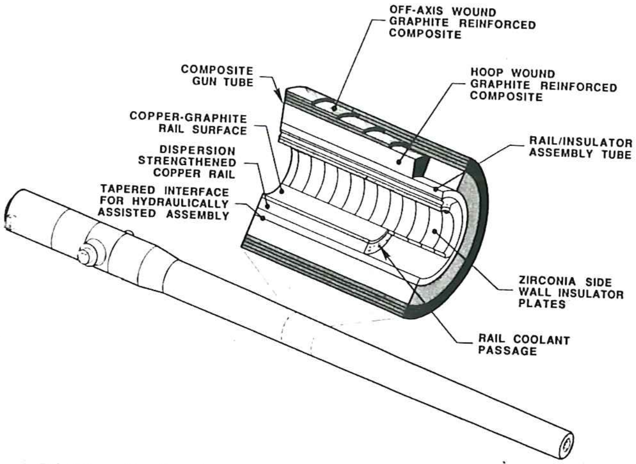

Figure 5. Task C electromagnetic gun barrel

A major advance in gun stiffness can be achieved if a ceramic proves suitable for use as the sidewall insulator material. A ceramic sidewall would also be beneficial in reducing bore erosion. The difficulty in using ceramic is its low tolerance for mechanical and thermal shock, and its low tensile strength. Transformation-toughened zirconia (TTZ) has excellent fracture toughness and thermal shock resistance. A series of "D" shaped TTZ plates stacked axially and bonded together to form a continous sidewall insulator is being considered. The question of tensile strength can be avoided if the material is kept in compression. This can be achieved if the rail and sidewall material can be suffiently preloaded in compression by the containment tube. A hydraulic assembly technique in which a fluid (possibly epoxy) is pumped into the interface between the rail/insulator assembly and the containment tube can provide the necessary preload.

Auxiliaries

The auxiliary system is composed of many subsystems which supply the needs of the prime power, pulsed power, and EM gun systems. The most basic of these subsystems supply lubrication, provide thermal management, and store the various coolants and fluids required. An auxiliary power unit (APU) is required to drive the lubrication pumps, provide startup power for the prime power turbine, provide electric power to the skid, and drive other miscellaneous units. A small gas turbine (a Pratt and Whitney PT-6), providing approximately 450 kw and weighing 160 kg, has been chosen as the APU. A summary of the auxiliary systems is listed in Table 2.

Conclusion

The Center for Electromechanics is under contract to design, fabricate, and test a lightweight EM gun system. The system will fire projectiles in the 2.5 to 4 km/s velocity range, providing 9 MJ of kinetic energy at the muzzle. This is roughly equivalent to the performance of a conventional 120 mm gun. The goal of the program is to prove the feasibility of using EM guns in an armored vehicle, and ultimately to produce an integrated 15 MJ EM gun system and vehicle. An air-core compulsator storing 150 MJ and producing a 4.4 MA pulse at a peak power of 26 GW is being developed. The project is significant in that it will have a major impact on future of EM guns for military applications.

Table 2. Auxiliary summary

Hydraulics

	Pressure (MP_a)	AVG Power (kW)
Compulsator bearings	20.7	224
turbine lubrication	1.4	0.8
Gearbox / Clutch lubrication	0.3	0.8
Misc. (Fan Motors, turbine starter, etc.)	41.4	56

Thermal Management

	Type	Rejection Rate (KW)	Expendibles
Armature winding	He(closed loop) /LN_2(open loop)	149	20.8 ℓ/shot
Field Coil	LN_2 (open loop)	149	9.5 ℓ/shot
Compulsator bearings	Oil / Air	589	-----
Turbine	Oil / Air	37	-----
Gearbox / Clutch	Oil / Air	75	-----
EM Gun	Water(closed loop)	550	-----
Misc.	Oil / Air	15	-----

Reservoirs

	Volume (ℓ)
Liquid Nitrogen (LN_2)	946
Helium (He)	37 (at 165 MP_a)
Water	57
Fuel	189
Bearing oil	757
Turbine oil	76
Gearbox / Clutch oil	379
N_2 (gas)	20 (at 0.8 MP_a)

Acknowledgment

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References

[1] U. S. Patent 4,200,831, W. F. Weldon, M. D. Driga, H. H. Woodson.

[2] W. L. Bird and H. H. Woodson, "Detailed Design, Fabrication & Testing of an Engineering Prototype Compensated Pulsed Alternator," Final Report, March 1980.

[3] M. L. Spann and W. L. Bird, W. F. Weldon, H. H. Woodson, "The Design, Assembly & Testing of an Active Rotary Flux Compressor," presented at the IEEE Conference, Albuquerque, NM, June 1-3 1981.

[4] M. L. Spann and S. B. Pratap, W. G. Brinkman, D. E. Perkins, R. F. Thelen, "A Rapid Fire, Compulsator-Driven Railgun System," presented at the 3rd Symposium on Electromagnetic Launch Technology, Austin TX, April 20-24, 1986.

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