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Abstract: A high-energy railgun range has recently been put into operation at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). Projectiles are fired straight down into a target chamber 45-m underground. Firing projectiles in a populated area, no matter how energetic or lethal, poses no hazard. The different components of the range--the railgun, the bore finishing and gauging system, the buswork, the breech connections--are designed not just for safety and to function well, but for operational convenience as well.

Introduction

A unique, highly instrumented range for development and testing of high-energy railguns and railgun projectiles and for aerothermal flight and impact physics experiments has recently been put into service at CEM-UT--a critical step in the development of earth-to-space launch and of new electromagnetic weapon systems for national defense (fig. 1).

Figure 1. The high-energy vertical railgun range at CEM-UT

In designing the facility, careful attention was placed on operational convenience. Experience to date confirms the convenience of operating the range, the railgun, and the in-flight projectile diagnostic system.

The railgun is mounted to fire downward into a 5 m diameter, 45 m deep shaft. The projectile flies through a 1 m diameter steel tube from the muzzle of the gun to the target chamber at the bottom of the shaft. An elevator moves people and light equipment. A 30 ton overhead crane moves heavy objects such as targets and railguns. Projectile diagnostic stations can be set up on any of the nine floors of the shaft.

The primary reason for a vertical range is safety; however, the vertical configuration facilitates, rather than hinders, operation.

The railgun is powered by the CEM-UT Balcones power supply, a bank of six high-energy homopolar generators.[1] Each generator charges an energy storage inductor; the inductors are commutated sequentially into the railgun with explosive opening switches[2]; the shape of the current pulse is determined by the sequencing.[3] At maximum speed (6,000 rpm) each generator stores 10 MJ of rotor kinetic energy (60 MJ total) which can be converted with 50% efficiency into stored inductive energy. At peak energy, each of the six inductors can deliver 1.2 MA of current.

A 3 m long, 45-mm railgun is in regular operation at present. A 10 m long, 90-mm railgun (expected muzzle energy: 9 MJ) is being assembled to replace the smaller gun. Our goal is to accelerate armor penetrating projectiles weighing from 1 to 3 kg to velocities from 2 to 4 km/s--about double the speed obtained with gunpowder.

Design Philosophy

A well designed and constructed railgun is obviously central to the success of a high-energy railgun facility. Large, energetic, destructive projectiles are fired in a facility located in a populated area; safety is an obvious concern. Not quite so obvious is the benefit of considering, early in the design, convenience of operation. The dividend is rapid turnaround, more experiments. The following list of topics and statements was constructed to guide the design:

- railgun structural design for stiffness,
- quick-change rails,
- rapid, convenient and accurate bore finishing (in situ)
- solid armatures are more efficient, and reduce bore damage,
- maintain ready access to the breech,
- do not overlook the need to carefully design the buswork,
- reliable, convenient, informative in-flight diagnostics.

The Railgun

Railguns are experimental devices requiring frequent rail assembly changes for maintenance or component testing. Most heavy duty railguns at CEM-UT [4] and at other laboratories have used bolted structural shells, laborious and time consuming to assemble and disassemble, and lacking stiffness.

The key to good railgun structural design is stiffness, structural rigidity to prevent excessive rail deflection under the enormous electromagnetic repulsion forces generated during firing. If the bore changes shape, an interference with the projectile may result [5], spoiling the acceleration and damaging the railgun. Rail deflection can prevent reliable sliding electrical contact between the rails and a solid armature. In arc-driven railguns or railguns using solid armatures which transition to arc drive, lack of structural rigidity may result in loss of rail-to-insulator sealing or loss of bore-to-projectile sealing. Seal failure results in the loss of high pressure plasma from the armature. To be sustained, the armature must be replenished by material extracted from the bore of the gun--the result is increased drag and increased bore damage. Another undesirable effect of poor rail-to-insulator seals is that vaporized material driven into the seams will condense and accumulate to eventually form a performance-robbing rail-to-rail shunt which diverts current from the armature.[4]

In general, increased structural strength and rigidity means more difficult and time-consuming assembly and disassembly. Not the hydraulically prestressed railgun, which achieves unprecedented stiffness yet is more maintainable than previous far less stiff designs. To change rail assemblies, depressurize the hydraulic sleeve, extract the old, insert the new and repressurize--all without removing the gun from its mountings. Stiffness is achieved by using high-modulus ceramic structural elements. Maintainability is a byproduct of hydraulic prestressing the ceramic for strength.[6,7]

Bore Finishing and Gauging

Rational tolerances on railgun bore size, shape, and straightness have not been established. Our experience has suggested the necessity of improving bore finishing techniques. Bore variations work against good sliding electrical contact between rails and solid armature, against maintaining the bore-to-projectile seal, and may contribute to bore damage resulting from ploughing or in-bore rattling.

Attempts to achieve a precise bore by carefully assembling accurately fabricated components into a gun requiring no post-assembly bore finishing have been disappointing in the past. Even if a technique for accurate first-time assembly existed, a bore refinishing technique would be required. A railgun used for the testing of new and untried armatures, projectiles and sabots will inevitably suffer inadvertent bore damage from time to time.

Installing and removing multi-megajoule laboratory railguns, designed for maintainability rather than portability, is time consuming. The devices weigh tens of tons. Just attaching or detaching the heavy-duty (multi-megampere) electrical power connections can occupy the better part of a day. The capability of in-situ refinishing of installed railguns has reduced turnaround time considerably.

Operating experience confirms that the attention and resources devoted to providing a capable, well-integrated bore finishing system were well spent. The design and operation of the bore finishing and gauging system are discussed in reference 8.

Solid Armatures

Our goal is to accelerate heavy (1 to 2 kg) projectiles to velocities beyond the capability of the gunpowder guns now in service--2 to 4 km/s.

Solid armatures [9,10,11] are well suited for this regime of operation. The incentive for development of solid armatures is increased electrical efficiency and reduced bore damage. Especially important is the ability to start heavy projectiles from rest without damaging the breech region of the gun. Solid armatures have worked well in the ultrastiff hydraulically prestressed railguns, and we anticipate continued improvement. We attribute the good performance to improved armature design, stiffness of the railgun and accuracy of the bore.

The solid armature testing program is described in reference 12.

Buswork

The acceleration of a kilogram projectile to a velocity of 4 km/s in a 10-m gun requires the delivery of mechanical energy to the projectile at a prodigious rate, three thousand megawatt or four million horsepower. The railgun is a linear electric motor capable of this level of performance, an electric motor whose primary virtue is utter simplicity. An electrical consequence of this simplicity is low impedance, a voracious appetite for current--multimillisecond, multimegampere pulses of current. The simple mechanical difficulties of transporting these currents through a 15-m bus are formidable. Fortunately, voltage is low--less than 10,000 V--a consequence of the railgun's low impedance, and a circumstance which greatly simplifies bus design.

An important requirement of a railgun bus is low inductance. This is especially important for a railgun powered by opening switch commutated storage inductors; low inductance contributes to switching efficiency.[13,14] The total inductance of a 10-m railgun, breech to muzzle, is about 4 μH ; hence, the inductance of the bus should not exceed several hundred nanohenries. Good insulation and low resistance ($<100 \mu\Omega$) are also required.

The bus must accommodate the mechanical loading resulting from repulsion between current flowing in conductors of opposite polarity. The method of choice for controlling inductance and mechanical loading is to laminate the bus, interleaving the polarities (fig. 2). Each plate carries current on the top surface and the bottom surface, except for the outermost two plates which carry current on their interior surfaces but not exterior. The laminated bus is equivalent to a two-plate bus of effective width

$$w_e = (n-1)w \quad n = 2, 3 \dots \quad (1)$$

If the effective width is large in comparison to the separation

$$\frac{s}{(n-1)w} \ll 1 \quad (2)$$

the electromagnetic characteristics of the bus are easily calculated:

Figure 2. Interleaved laminations reduce bus magnetic pressure and inductance

$$L = \frac{\mu_0 s}{(n-1)w} \quad (3)$$

$$P = \frac{\mu_0 I^2}{2(n-1)^2 w^2} \quad (4)$$

where μ_0 is the magnetic permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ H/m), s is the plate separation, w is the plate width, I is the current, L is the inductance per unit length and P is the repulsion force per unit of area (the magnetic pressure) acting on the conducting surfaces (fig. 3).

Figure 3. Magnetic pressure acting on the bus laminations

The bus which connects the output manifold of the Balcones power supply is 15-m long and consists of two balanced, independent five-plate buses (plate width 0.8 m, separation 2 mm, plate thickness 6 mm). No doubt a suitable design could be achieved using plates thinner than 6 mm. We chose a thickness of 6 mm (which can be tapped) to facilitate electrical connections to the bus. Since the mating plates of the independent buses are of the same polarity, the effective number of plates for the combination is nine. Under normal operating conditions, the bus current would not exceed 3.2 MA, the rated current of the 90mm hydraulically prestressed gun based on structural strength. If, however, all six opening switches were inadvertently fired simultaneously at full energy, instead of sequentially, a peak current of 7.2 MA would be delivered. The bus is designed to safely accept the full fault current. The installation of a sentinel to immediately fire the breech crowbars if the rating of the gun is accidentally exceeded is under consideration.

At fault current, the bus magnetic pressure is about 500 kPa (70 psi). The low magnetic pressure suggests the bus plate can be assembled with adhesive.[15] We chose to clamp the bus mechanically (fig. 4) for simplicity, to accommodate a tight schedule and to provide for possible disassembly. However, adhesive assembly of laminated high-current busses is a promising technique for the future, especially in cases where the magnetic pressure is low enough to allow the use of room temperature cured or pressure sensitive adhesives. The low magnetic pressure achieved by using many wide laminations simplified the structural analysis of the bus. The maximum bending stress resulting from magnetically driven deflection of an exterior plate is

$$\sigma = \frac{\mu_0 I^2 S_c^2}{4(n-1)^2 w^2 t_p^2} \quad (5)$$

where S_c is the unsupported span between clamps and t_p is the plate thickness. Equation 5 is based on a static load. A clever designer considering a critical application could refine the design by considering the dynamic nature of the loading (reference 16, chapter 15, for example). The plates of the interior polarity are less wide than the exterior polarity. A filler (fig. 5) is inserted in the resulting groove to seal out dust and dirt, preventing arcing between polarities.

We found that once the bus was designed for structural simplicity, no further modification of the design was required to reduce the already low inductance and resistance.

Breech Access

From the outset, we were determined to maintain ready access to the breech, to load the projectile or to hone the bore without having to disconnect and reconnect the heavy-duty power leads to the gun, and to maintain ready access to the explosively operated breech crowbars for convenient reloading.

This strategy also keeps open the option of bolt-on breech accessories such as gas or electric projectile injectors, prototype autoloaders or external plasma injectors for arc drive.

Past experience has shown that the electrical transition from the bus to the rails is a problem area, deserving as much attention and careful design as the railgun itself. The primary requirements for

Figure 4. The bus is an important component of the system. The cylindrical object in the center is the manifold to which each of the six explosively-operated opening switches delivers current. The taller cylinders are storage inductors. When fully assembled, there are six independent equally-spaced storage inductors, one for each homopolar generator.

Figure 5. Sealing out dust and dirt to prevent electrical breakdown between polarities

the transition section are low inductance, mechanical strength and secure (nonarcing) electrical contact with the rails. We have added the additional requirement of breech access. The design of the breech connections is described in reference 7.

The readily accessible breech region (fig. 6) has made a substantial contribution to the overall operating convenience of the system.

Figure 6. The breech of the railgun is readily accessible. Note that the electrical connections are perpendicular to the axis of the gun

Safety of Operation

As originally conceived, the firing range was horizontal, armored to contain errant projectiles. As the design proceeded, it became apparent that the 40-m long horizontal flight range, rated for the firing of armor penetrating projectiles in a populated area, was too expensive, and that operation of the projectile flight and impact diagnostic system (setting up high speed cameras and flash X-rays, changing targets) would be severely hindered in a heavily armored horizontal range. Two choices emerged: a much-shortened armored horizontal flight range (5 or 10 m) or a 45-m vertical range. As the design evolved, the vertical range became increasingly attractive and was selected for construction. The deciding factors were absolute safety against errant projectiles, lower cost, convenience of operation and ready upgrading for higher energy projectiles.

That the projectile flight and impact diagnostic system is conveniently operated in the multi-floored vertical range is confirmed by operating experience. Results of projectile flight and impact diagnostic experiments are given in reference 17.

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References

- (1) W.L. Noble, J.M. Weldon and J.H. Gully, "Final Manufacture and Assembly of a Modular 60 Mega-joule Pulsed Homopolar Power Supply," *IEEE Transactions on Magnetics*, vol Mag-22, 1986, pp 1623-1627.
- (2) R.L. Sledge, D.E. Perkins, and B.M. Rech, "High Power Switches," 4th Symposium on Electromagnetic Launch Technology, Austin, TX, April 12-14, 1988.

- (3) R.C. Zowarka, D.R. Peterson, J.H. Price, and W.F. Weldon, "EMGWS Task B Program at The University of Texas at Austin," 4th Symposium on Electromagnetic Launch Technology, Austin, TX, April 12-14, 1988.
- (4) D.R. Peterson, D.A. Weeks, R.C. Zowarka, Jr., R.W. Cook, and W.F. Weldon, "Testing of a High-Performance, Precision-Bore Railgun," IEEE Transactions on Magnetics, vol Mag-22, 1986, pp 1662-1668.
- (5) D.R. Peterson, C.M. Fowler, C.E. Cummings, J.F. Kerrisk, J.V. Parker, S.P. Marsh, and D.F. Adams, "Design and Testing of High-Pressure Railguns and Projectiles," IEEE Transactions on Magnetics, vol Mag-20, 1984, pp 252-255.
- (6) E.P. Fahrenthold, D.R. Peterson, J.H. Price, and A.Y. Wu, "Stress Analysis for Design of Electromagnetic Launchers," Journal of Vibration, Acoustics, Stress, and Reliability, vol 110, 1988, pp 395-400.
- (7) J.H. Price, E.P. Fahrenthold, C.W.G. Fulcher, D.R. Peterson, W.F. Weldon, and R.C. Zowarka, "Design and Testing of Large-Bore, Ultra-Stiff Railguns," 4th Symposium on Electromagnetic Launch Technology, Austin, TX, April 12-14, 1988.
- (8) D.R. Peterson, M.W. Harville, W.F. Weldon, R.C. Zowarka, Jr., and J.H. Price, "Producing and Gauging Precision Railgun Bores," 4th Symposium on Electromagnetic Launch Technology, Austin, TX, April 12-14, 1988.
- (9) D. Kuhlmann-Wilsdorf, "Theoretical Speed and Current Density Limits for Different Types of Electrical Brushes," IEEE Transactions on Magnetics, vol Mag-20, 1984, pp 340-343.
- (10) J.P. Barber and C.L. McDonald, "A Comparison of Armature Performance," IEEE Transactions on Magnetics, vol Mag-20, 1986, pp 1389-1394.
- (11) G.L. Ferrentino and W.J. Kolkert, "On the Design of an Integrated Metal Armature and Sabot for Railguns," IEEE Transactions on Magnetics, vol Mag-20, 1986, pp 1470-1474.
- (12) J.H. Price, C.W.G. Fulcher, M.W. Ingram, D.E. Perkins, D.R. Peterson, R.C. Zowarka, and J.A. Pappas, "Design and Testing of Solid Armatures for Large-Bore Railguns," 4th Symposium on Electromagnetic Launch Technology, Austin, TX, April 12-14, 1988.
- (13) E.M. Honig, "Repetitive Energy Transfers from an Inductive Energy Store," Ph.D. Dissertation, Texas Tech University, August, 1984.
- (14) H.H. Woodson and W.F. Weldon, "Energy Considerations in Switching Current from an Inductive Store into a Railgun," 4th IEEE International Pulsed Power Conference, Albuquerque, NM, June 6-8, 1983.
- (15) B. Maas, "EM Gun Facilities and Research," Presented at the 2nd Meeting of the Electromagnetic Launcher Association, Pomona, CA, July, 1986.
- (16) R.J. Roark and W.C. Young, Formulas for Stress and Strain, fifth edition, McGraw-Hill, New York, 1982.
- (17) M. Castoe, B. Firey, J. Lynch and F. Mayer, "Operation of a Ballistic Range for 9 MJ Tactical Railgun Testing," 4th Symposium on Electromagnetic Launch Technology, Austin, TX, April 12-14, 1988.