Testing of the Cannon Caliber Rapid Fire Railgun

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Abstract—A rapid fire launcher has been designed, built, and tested in single-shot mode for the Cannon Caliber Electromagnetic Gun (CCEMG) System. The 2.25-m long railgun has a rectangular cross section (30 mm round bore equivalent) and has a series, two-turn augmented rail configuration. The gun is designed for rapid fire operation; three, five round salvos of 185 g integrated launch packages (ILPs) accelerated to 1,850 m/s with a minimum time between salvos of 2.5 s. Launch packages will be autoloaded at a repetition rate of 5 Hz via a hydraulic mechanism capable of up to 3,000 lb insertion forces. The railgun support structure and flexible buswork permit the railgun to recoil approximately 2 cm to mitigate the electromagnetic repulsion loads. Multiple 830 kA pulses provided from the CCEMG compulsator power supply require the gun to be liquid cooled for thermal management.

Diagnostics for the single-shot tests include B-dots, flux rulers, voltage, and current measuring sensors. Other launcher diagnostics include rail conductor temperatures, coolant temperatures, and railgun preload mechanism (flatjacks) dynamic pressures. This paper presents the test results and general gun performance observations for single-shot, compulsator powered experiments.

INTRODUCTION

Commissioning testing of the Cannon Caliber Electromagnetic Gun (CCEMG) system is proceeding. The CCEMG system consists of the compensated pulsed alternator (CPA) power supply [1], power electronics [2], and the electromagnetic EM launcher which is the focus of this paper. The railgun design parameters are listed in Table I. The railgun is 2.25 m long with an augmented turn in series with the

main rails. The railgun bore geometry is rectangular: 1.75 cm $\times$ 3.94 cm (Fig. 1). The rapid fire railgun is mounted to a high performance autoloader which provides compliant structural mounting and 15 integrated launcher packages (ILPs) at a rate of up to 300 ILPs per minute.

The CCEMG railgun incorporates several unique features: ceramic sidewalls, directional preloading, and liquid cooling [3]. These features combined make the Cannon Caliber railgun structurally stiff and lightweight. Testing to date has demonstrated an effective inductance gradient of 1.0 $\mu\text{H/m}$ and high breech efficiencies. A developmental approach was adopted by the program to evaluate the gun's structural design while studying the performance of several ILP concepts. As a result, two single shot guns were built (referred to as launcher IIA and IIB) in addition to a water-glycol cooled, rapid-fire gun (launcher III). This paper presents test results from initial testing of launcher III at The University of Texas Center for Electromechanics (UT-CEM). Test results from launcher IIA are reported by Zielinski [4].

Table I. Cannon caliber railgun specifications

Performance	
Launch package mass	185 g
Muzzle Velocity	1,850 m/s
Muzzle Energy	316 kJ
Inductance Gradient	1.0 $\mu\text{H/m}$
Peak Current	835 kA
Number of salvos	3
Rounds/salvo	5
Firing rate	5 Hz
Time between salvos	2.5 s
Physical	
Railgun Type	Series Augmented
Bore Dimensions	Rectangular 17.5 x 39.4 mm
Overall length	2.25 m
Augmented length	1.85 m
Structural stiffness at peak current	0.2% deflection
Coolant	Water-ethylene glycol
Weight	270 kg

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Fig. 1. CCEMG launcher cross section

POWER SUPPLY

The Cannon Caliber power supply is a self excited, air-core compulsator capable of delivering 830 kA to the railgun for three, five round salvos at a shot rep-rate of 5 Hz. The compulsator stores 40 MJ at 12,000 rpm and weighs only 4,500 lb (2,045 kg). The compulsator and railgun performance levels and geometries were optimized to produce a highly efficient system to deliver ILPs to a muzzle energy of 316 kJ. Fig. 2 shows a circuit schematic of the CCEMG system. One hundred and sixteen CCEMG system tests have been performed. The tests have included compulsator mechanical spin tests, open circuit voltage tests, short circuit tests with the gun muzzle shorted, and single-shot testing with the railgun.

RANGE

Launcher III testing was performed in what was previously known as the iron core compulsator range using the CCEMG power supply. The gun is fired into an 8.0 m long, steel flight tube located inside concrete bunkers (Fig. 3). The flight tube holds the velocity "make-screens" and a target chamber where "soft catches" are attempted. The range is backed-up with 0.6 m of armor plate.

AUTOLOADER

The CCEMG autoloader is a high performance, fully automated ammunition-loading system utilizing state-of-the-art hydraulics. The two primary functions of the autoloader are to provide mounting and interfaces to the launcher and to automatically load ILPs.

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Fig. 2a. Launcher III

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Fig. 2b. Launcher, autoloader, and UT-CEM range

The autoloader includes a rigid mounting structure with integrated guide arms to support the launcher. This combination (along with a tunable recoil system) minimizes structural loading as well as mount induced shot-to-shot dispersion. To facilitate gun recoil, linear bearing bushings were built into the launcher structure and precision machined parallel to the gun's axis. Provisions for small train and elevation adjustments are also included.

A compliant electrical bus connection is accomplished by hexapolar cables. Bulkhead gang connectors are used to terminate the cables at the solid state gun switch and launcher.

Various system requirements resulted in the need for a high performance, state of the art automated loading system.

Fig. 3. CCEMG circuit schematic

Some of these requirements include:

Rate of fire:	300 rounds per minute
Projectile capacity:	15 ILPs
Projectile insertion force:	3,000 lb (674 N)
Projectile motion distance:	22 in (0.56 m)
Environment:	Transient EM fields

These requirements resulted in a 5,000 psi hydraulic automated loading system. The rammer is a 22 in. (0.56 m) stroke hydraulic actuator which controllably cycles (extend and retract) in 100 ms. The result is an extremely high speed (1,200 in./s), high power (1,250 hp), and high pressure (15,000 psi buffing spikes) system. The clip system indexes ILPs to the ramming position. The actuation system is comprised of two 5,000 psi hydraulic "stitching" actuators which controllably index ILPs to the ramming position in 30 ms. The CCEMG autoloader has been tested at maximum rate of fire with a single ILP with a mock-up of the launcher.

LAUNCHER STRAIGHTNESS MEASUREMENTS

Straightness measurements of the gun's bore were made routinely during launcher fabrication. Bore straightness is

measured with an optical telescope and a precision spring loaded target incrementally pushed through the bore. This measurement process has demonstrated a repeatability of ± 0.001 (0.03 mm). Straightness measurements are a good indication of the integrity of the adhesive bonds between the rails and sidewall as well as the symmetry of the structural preload. A target was built to attach to the autoloader's rammer in order to align the loading mechanism with the gun. Alignment corrections were made by adjusting the shim thicknesses between the support structure and the gun linear bearing mounts. The final alignment between the autoloader and launcher and the true bend of the gun are illustrated in Fig. 4. The gun has a true bend of approximately 0.010 in. (0.3 mm) over 2.25 m. Launcher III's straightness values are consistent with the those measured on launchers IIA and IIB.

SINGLE SHOT TESTING

The purpose of the single-shot testing is to commission the pulse power system, verify the computer simulation to actual performance, and establish reliability of the control system. To conserve time and program cost, minimal range diagnostics are utilized. Once the commissioning objectives are achieved, multishot testing will begin with incremental increases in system energy.

Six "single-shots" have been performed. Table II summarizes the results from the four shots of significance (shots #3 to 6). Launcher performance diagnostics include: flux rulers, B-dots, breech (main and augmenting rail) voltage, muzzle voltage, current Rogowski, three "make-screens," and a yaw card 6-m downrange. Mechanical diagnostics include thermocouples located near an augmenting and main rail and two PCB pressure transducers to measure dynamic pressures in the upper and lower flatjacks. Analog pressure gages mounted to an electrically isolated panel permit continuous monitoring of all four flatjack pressures (upper and lower for the primary and secondary). Each flatjack and supporting hydraulic circuit is electrically isolated from each other, ground, and the gun circuit.

The current and muzzle voltage plot for shot #5 are shown in Fig. 5. Peak current for shot #5 was 605 kA. Current is measured with a Rogowski coil which is built into the breech of the gun. The Rogowski was calibrated using a $20.15 \mu\Omega$ current viewing resistor (CVR) connected to the muzzle of the gun. Short circuit discharges through the CVR were performed up to 165 kA. The muzzle voltage plot for shot #5 shows a characteristic plot of the augmented gun. The last 0.2 ms prior to armature exit represents the "non-augmented" portion of the gun and indicates a peak armature drop voltage of 120 V.

Breech efficiency is defined as the kinetic energy of the armature divided by the energy delivered to the breech of the gun. For shot #5, the breech energy as determined by integrating the product of the breech voltage and current is 388 kJ

at armature exit (Fig. 6). Based on the velocity of 1,530 m/s verified with B-dots, muzzle exit, and the make-screens and assuming no loss of armature mass, the breech efficiency for shot #5 was 49%. The high breech efficiency is attributed to an optimized barrel and power supply [5],[6]. A significant amount of the breech power is reclaimed by the compulsator in the form of stored energy in the rotor. Exiting at or near current zero minimizes the magnetic energy lost in a muzzle arc. Obviously, this is also important for minimizing EM and audible signatures. For this reason, the muzzle of the gun was designed to support an optional solid state muzzle switch.

The effective launcher inductance gradient (L'_{eff}) for each shot is calculated using the integral of the current squared and the velocity data. An average value of $1 \mu H/m$ was obtained for all tests. This value was also verified by tests performed at Aberdeen Proving Grounds and UT-CEM on launcher IIA. [4]

Shot #6 represents the highest muzzle energy (279 kJ) demonstrated by launcher III. A 155 g solid armature projectile was fired at 1,900 m/s with a peak gun current of 660 kA. The projectile being fired for all single-shot tests is a simple 7475-T651 aluminum "slug" with a tungsten all-thread insert for customizing the projectile mass (Fig. 7). The armature utilizes a tapered interference to maintain an optimum contact force with the rail surfaces. To obtain muzzle performance at this CPA speed and excitation level, a high muzzle current (207 kA) had to be tolerated. The muzzle switch was not implemented for these tests.

Fig. 4. Launcher III and autoloader alignment plot

Fig. 5. Current and muzzle voltage, shot#5

Table II. CCEMG selected single shot test summary

Parameter/Shot, Run # & Date	Units	Shot#3 Run#107 1/24/96	Shot#4 Run#114 2/5/96	Shot#5 Run#115 2/7/96	Shot#6 Run#116 2/9/96
CPA Parameters					
CPA Rotor Speed	rpm	7,580	8,021	8,000	8,264
FIM Charge	kV	2	2	2	3
Field Amps	kA	22.0	27.4	27.4	30.5
% Design Field	%	88	110	110	122
Field Rise Time	s	0.192	0.195	0.195	0.160
CPA Peak AC Volts	V	1,910	2,510	2,485	2,835
Rotor Speed @ Discharge	rpm	7,251	7,607	7,653	7,772
Fire Angle (electrical)	°	5	5	5	5
Volts @ Trigger	V	166	221	221	220
Peak Gun Current	kA	496	599	605	660
Pulse width	ms	3.30	2.97	2.97	2.97
Launcher/Armature Parameter					
Primary Flatjack Pressure	ksi	10.0	13.0	13.0	15.0
ILP Mass	g	135.3	148.4	163.3	154.5
Load Force	lbf	3,100	3,200	3,360	3,136
ILP Muzzle Velocity	m/s	1,187	1,729	1,530	1,900
Muzzle Energy	kJ	95.3	222	191	279
Action	MA ² s	322	495	512	589
Breech Efficiency	%	44	53	49	49
Muzzle Current	kA	0.0	125	68	212
Launcher L'	μH/m	1.00	1.04	0.98	1.00

GUN OBSERVATIONS

The single-shot solid armature projectiles are loaded manually using a hydraulic cylinder to accurately monitor insertion force. Insertion force is nominally 3,000 lb. Gun maintenance between shots consists of cleaning out the previous shots deposited aluminum from the rail surfaces and sidewalls. This operation is performed using a set of diamond lapping tools; one for the sidewalls and one for the rails. A bore video camera is routinely used to inspect the bore. No rail or sidewall damage has been observed with the exception of minor arc erosion at the muzzle from shot #6 (207 kA muzzle current). No hypervelocity gouging or pitting has been observed.

The primary flatjack pressures were increased to 15 ksi for shot #6. Dynamic pressure measurements of the primary flatjacks have not indicated pressure increases during a shot. Temperature measurements of the main and augmenting rails are as anticipated, insignificant until rapid fire testing commences. Launcher coolant lines were not connected to the gun for single-shot testing. During shot #6, the gun recoiled approximately 0.375 in. (1 cm) as indicated by a grease ring on one of the two recoil cylinders.

Fig. 6. Gun power and gun energy, shot #5

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Fig. 7. CCEMG single shot test armature

CONCLUSION

An overview the CCEMG launcher and autoloader has been presented. Launcher straightness and alignment with the autoloader has been described. Six single-shot tests have been performed and breech efficiencies and effective inductance gradients have been calculated. Peak current in the launcher for the high performance test (shot #6) was 660 kA resulting in a muzzle energy of 279 kJ. Preliminary CCEMG single-shot railgun tests are encouraging and indicate that the gun is operating as designed. CCEMG commissioning tests are ongoing.

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