SALVO FIRE EXPERIMENTS USING A 0.60 CALIBER ELECTROMAGNETIC LAUNCHER

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Salvo Fire Experiments Using a 0.60 Caliber Electromagnetic Launcher

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Abstract--The Center for Electromechanics at the University of Texas (CEM-UT) is in the testing phase of a contract to develop a laboratory based, small caliber electromagnetic launcher (EM) and compulsator power supply. The goal of this program is to accelerate three, 32-g masses to 2 km/s at a 10 Hz firing rate. A 0.60 caliber, series augmented, 1.6 m launcher has been fabricated and tested. The launcher testing utilized the iron core compulsator (ICC) power supply and the 400 kA small caliber SCR switch. The extended pulse width of the ICC when firing the shorter small caliber launcher would ordinarily lead to a large muzzle arc. Using a muzzle shunt resistor on the augmented launcher the muzzle arc can be substantially reduced. An added benefit is the ability to determine the state of the armature in the augmented launcher. By measuring the current in the muzzle shunt resistor, the transition point of the armature in the launcher bore can be found. A high-pressure pneumatic autoloading mechanism provides salvo fire capability for the solid armature driven projectiles.

This paper presents a description of the launcher, SCR switch, muzzle shunt resistor, ICC power supply, and autoloader. A description of the control apparatus used to synchronize the autoloader, SCR switch, and launcher is given. Data from several double shots and one triple shot is also presented. This data includes launcher data, SCR switch data, muzzle shunt resistor current traces, and autoloader performance measurements for firing rates of up to 13.5 Hz.

INTRODUCTION

The small caliber compulsator (SCC) system is designed to advance EM launch technology from the laboratory to the field. Both the compulsator and the launcher are high power-to-weight ratio designs that utilize existing technology [1],[2]. The goal of a three-shot salvo at a 10 Hz firing rate take full advantage of the inherent ability of a compulsator to provide repetitive high energy pulses in a small package [3]. The complexity of this task is further reduced due to the use of a single solid state switch in the overall EM system. Prior to the SCC fabrication, the small caliber launcher, solid state switch, pneumatic autoloader, and control circuitry were fabricated and tested. This advance testing verified the individual components as well as the overall system design.

To fully integrate the entire salvo fire system, the ICC was chosen for the power supply. The ICC was designed for a ten-shot salvo fire with 1 MJ pulses at a firing rate of 60 Hz. This capability is well beyond the three 364 KJ pulses needed to fire the small caliber railgun. However, the ICC

was designed to fire a non-augmented railgun that is 3 m in length. The higher inductance and 1.6 m length of the SCC railgun does not allow optimum operation of the ICC power supply. When simulating the ICC with the SCC railgun, it was discovered that a large muzzle current (150 to 250 kA) is present when the projectile exits the launcher. To mitigate the destructive effects of this muzzle arc, a muzzle shunt resistor was employed with good results. The existing firing control hardware and data acquisition capabilities available with the ICC system provided additional incentive to use this power supply

RAILGUN

The SCC railgun is a series augmented design with a 0.60 caliber bore (fig. 1). The primary rail materials that have been investigated are molybdenum and dispersion strengthened copper, with a third barrel under construction with TZM primary rails. The augmenting turn is constructed of ETP 110 copper insulated from the primary rails with b-stage preimpregnated fiberglass cloth. The entire package is contained in a 301 stainless steel laminated structure. The launcher breech thickness is minimized by utilizing a laminated structure to connect the upper augmenting turn to the lower primary rail as well as connect the launcher to the power supply. Minimizing the breech thickness results in a shorter stroke requirement on the autoloader and a faster loading rate.

The treatment of the muzzle end of the launcher was reduced to finding a scheme which would insure commutation of the current at the muzzle in a nondestructive manner. Two possible solutions were investigated: (1) a

Fig. 1. Small caliber launcher cross section

muzzle crowbar switch, and (2) a muzzle shunt resistor. Both of these elements would provide a path for the current to flow without a significant muzzle flash. After analysis, the muzzle shunt resistor was chosen due to the inherent simplicity and lack of complicated switching controls.

Providing a conductive path across the muzzle of an augmented launcher performs differently compared to that of a simple railgun. In a simple railgun, that path would not carry any significant current until the projectile began to exit from the launcher and the muzzle began to arc. In a simple railgun, the only current that would flow through this conductive path is that which corresponds to the voltage drop across the solid armature, which is small. Fig. 2 shows the circuit of the augmented railgun. The circuit formed by the armature, rails, and the muzzle resistor links the flux produced by the augmenting turn at all times. Resulting flux linkage differs according to the velocity of the projectile. Initially, when the velocity of the projectile is low, the muzzle shunt resistor (MSR) behaves like a compensating circuit and a current flows in this circuit in the opposite direction to the current in the augmenting loop. As the velocity of the projectile increases, the augmenting flux linking the MSR gets trapped and is compressed as the projectile moves down the barrel and the inductance of the muzzle resistor circuit decreases. The result is the current in the MSR begins to increase in the same direction as the augmenting turn current to maintain a near constant flux linkage. The MSR is sized so the current in the unit will rise to a value almost equal to the current in the main rails so the current through the armature at exit is small. After exit, any remaining current flow through the armature commutates into the MSR circuit and further reduces the damage to the rails as seen in fig. 3.

The MSR current data can also be used as a diagnostic tool to aid in the designing of projectiles in an augmented launcher. The primary means of detection of a transitioning solid armature in a railgun bore is the muzzle voltage. However, in an augmented launcher this data is not a reliable indicator of armature transition. With the MSR and B-dot data, the velocity at transition can be identified. When the solid armature transitions, the resistance across the armature contacts increases which increases the current flowing into the MSR. This is represented by an inflection in the MSR current trace as seen in fig. 4.

Fig. 2. Circuit schematic of the muzzle resistor test setup

AUTOLOADER

The autoloader is essentially a single-ended double acting cylinder which was designed for 3,000 psi inert gas usage (fig. 5), and is designed to load the 400 lb preload armatures a distance of 10 in. at a rate of 10 Hz. A 285 in.³ accumulator is pressurized prior to the autoloader operation. This accumulator feeds into a manifold block which distributes the high pressure gas to the solenoid operated, forward, reverse, and magazine control valves. The valves chosen were MV100 2-way valves manufactured by Marotta Scientific Controls. The forward and reverse control valves feed into the cylinder end plates which contain manifolds and check valves for proper switching of the working fluid. The third control valve operates the magazine which is constructed of a high strength thermoplastic material. This magazine is operated by a single ended single acting cylinder and provides up to 500 lbf for switching the magazine during launcher firing. The magazine position is indicated by the

Fig. 3. Simulation of the full-performance test with muzzle resistor and no armature transition

Fig. 4. Muzzle resistor current with transition induced inflection point

use of a fiber optic position indicator. Two more indicators are used to sense the position of the loading piston. These three fiber optic sensors feedback to the autoloader control electronics which communicate with the firing control circuitry [4]. Initial testing of the autoloader indicated a potential firing rate of 20.5 Hz using helium as the working fluid. This testing was done without any armatures or armature preload present. The limiting factor for the autoloader cycle frequency was the time required to open and close the solenoid valves and the size of the opening in the valves.

The autoloader control circuitry is located in the shielded screen room with the other compulsator control circuits. The three employed optical sensors indicate: (1) loading rod fully withdrawn, (2) loading rod fully extended, and (3) magazine in position for third loading cycle. Combinational logic assures proper operation and sequencing of the loader. The compulsator discharge controller was revised to add a disable input. This is activated by the loader circuit when a load sequence is begun and will be deactivated when the pusher rod is being withdrawn after a successful load. Any irregularity in the load sequence will cause the disable to remain activated. The loader circuit includes light-emitting diodes (LEDs) to annunciate both status and fault detection. Fig. 6 shows the block schematic of the loader circuit.

SCR SWITCH

The launcher circuit thyristor switch was designed to alleviate the requirements placed on the autoloader mechanism. Without this switch the autoloader would have to operate on the compulsator cycle speed. The switch itself has sixteen legs connected in parallel as seen on the left in fig. 7. A single SCR in each leg has 3.4 kV recovery, and sees 24 -kA peak current in salvo mode. The switch was initially assembled and tested using SCRs made by International Rectifier, Ltd. (IRC) of Canada. During low level tests of 45kA, data indicated a +/- 23% deviation in the current sharing between SCRs. Suspecting a bad lot selection of SCRs, sixteen 2 kV devices manufactured by

4101.0222.1

Fig. 5. Autoloader circuit schematic

4101.0335

Fig. 6. Block schematic drawing for autoloader control circuit

s4101.335

Fig. 7. 400 kA SCR switch shown on left

Westcode were installed and tested with the same results. Upon closer examination of the data a pattern developed indicating poor inductance matching in the switch buswork. A simple modification of the switch body will solve this problem, however, the switch has performed to 320 kA without exceeding any SCR design parameters.

EXPERIMENTS

The various components which make up the salvo fire system were checked out during several single shots prior to the first repetitive fire attempt. After the single shots, the autoloader was cycled in various fault mode conditions to test the compatibility with the various ICC control circuits. The ICC was then discharged in a three-pulse configuration at approximately 30 kA with the autoloader live and with no projectiles. This test verified the synchronization between the autoloader timing and the firing sequence controller.

Test #1

The first test was to fire two projectiles at the 200 kA level. This test would determine the effects of debris on the magazine and autoloading mechanism. The first projectile was loaded into the launcher using the autoloader. One projectile was inserted into the magazine and placed in the ready position in the clip. Both 32-g projectiles were fired with the current reaching 191 kA. The measured velocity was approximately 750 m/s for the first projectile. The second projectile was fired 160 ms later. The velocity break screens were expended on the first projectile and the fast data acquisition equipment did not have the memory to extend to 160 ms. Therefore, no velocity data was available for the second projectile. The switch voltage and current pulse traces indicated no anomalies in the second projectile.

Test #2

Due to the success of the double shot, the next attempt was for a triple shot. The first projectile was loaded into the launcher using the autoloader. The magazine was then loaded with two projectiles and inserted into the clip between the autoloader and the launcher breech. This test required the use of the magazine loading cylinder and magazine to shuttle the third projectile into position. The first projectile was fired from the launcher while simultaneously starting the loading cycle for the second projectile. The second projectile was fired approximately 203 ms after the first. The third projectile was not fired due to a sequencer programming error in the fire control system. The slow operation of the autoloader was discovered to be a faulty seal in the autoloader. The first projectile achieved a velocity of 950 m/s. The velocity of the second projectile was not measured, however, no differences existed in the current traces and it is inferred the velocities of both projectiles were comparable.

Test #3

This was the second attempt to do a triple shot with the small caliber launcher and autoloader using the ICC power supply. The experimental setup was identical to test #2. The first projectile was fired from the launcher while simultaneously starting the loading cycle for the second projectile. The second projectile was fired 74 ms after the

first. The third projectile was not fired due to a debris fouled optical sensor on the autoloader. The projectile velocities were measured at 1,000 m/s.

Test #4

This was the third attempt to do a triple shot with the small caliber launcher and autoloader using the ICC power supply. The experimental setup was identical to test #3. The first projectile was fired from the launcher while loading the second projectile. The second projectile was fired 74 ms after the first. The magazine indexed correctly and loaded the third projectile, however the autoloader enable circuit timing was not adjusted properly. The improper adjustment disabled the firing sequence controller and prevented a compulsator discharge. The projectile velocities were again 1,000 m/s.

Test #5

This was the fourth and first successful attempt to do a triple shot with the small caliber/ ICC experimental setup. An adjustment to the autoloader/firing sequence controller synchronization allowed the compulsator to fire three, 32-gram projectiles. The second projectile was fired 74 ms after the first; the third projectile, 191 ms after the first. All three projectiles were recovered with minimal damage. The launcher current for the first shot was 203 kA. Launcher currents for the second and third shots were 190 kA due to decay in the field current. The first projectile obtained a velocity of 1,000 m/s. The high-speed camera data verified the timing on all three shots. The velocity of 1,000 m/s was also substantiated for all three shots. Average autoloader performance was 10.5 Hz (13 Hz for shot 1 to 2; 8.5 Hz performance for shots 2 to 3). The launcher current and switch voltage versus time is shown in fig. 8. Individual muzzle, total and launcher current versus time is shown in figs. 9 thru 11.

Fig. 8. Launcher current and switch voltage data for triple shot

Test #6

This was an attempt to increase the muzzle energy for a three-shot salvo. Due to complications in the ICC power supply the rotational speed was limited to 2,200 rpm. The muzzle shunt resistor was removed to allow the pulse from the compulsator to drive the transitioning armatures down the launcher bore. The first projectile exited the launcher at approximately 3.35 ms. The second projectile was launched 175 ms after the first. The absence of the muzzle shunt resistor provided excessive residue to be deposited on the magazine assembly at the launcher breech. This jammed the clip mechanism and the third shot could not be fired. The measured velocity of the first projectile was 1,700 m/s, the second projectile velocity could not be measured.

Fig. 9. Armature current, total current and muzzle resistor current for pulse 1 of 3

Fig. 10. Armature current, total current, and muzzle resistor current for pulse 2 of 3

Fig. 11. Armature current, total current, and muzzle resistor current for pulse 3 of 3

CONCLUSIONS

A design for high-speed salvo fire system has been developed. Several important issues were addressed with these experiments:

- (1) The integration and testing of the launcher, autoloader, SCR switch, and controls will allow easy transition into the next generation small caliber compulsator power supply.
- (2) No projectile performance degradation was seen in any of the salvo fire experiments.
- (3) The firing rate of a compulsator based system is limited only by the autoloader design, pulse frequency from the compulsator, and thermal operating limits.
- (4) Debris management at the launcher breech is simplified by minimizing the muzzle flash.

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