Railgun Instrumentation

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7th EML Symposium on Electromagnetic Launch Technology
San Diego, CA
April 20-24, 1994

PR - 191

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Abstract — In recent years, the railgun focus has switched to developing tactical weapons with launch velocities of 2 to 3 km/s. The projectile focus for tactical weapons has switched from plasma to solid armatures because of their high efficiency. Since few measurements have been made on the state of the solid armature during an electromagnetic launch, new diagnostics need to be developed to substantiate theoretical models. This paper presents several recent developments at CEM-UT in the area of railgun instrumentation that attempt to directly or indirectly measure physical quantities that relate to the function of a solid armature during a launch.

INTRODUCTION

As the technology advances in the area of electromagnetic launchers and launch packages, so must the diagnostics used to record the data from tests. Testing being performed at CEM-UT on the 90 mm bore gun is concentrated on the development of a highly efficient launch package capable of delivering a penetrator on target at 9 MJ. In order to improve the launch package design, there must be a basic understanding about what happens to the package during the launch sequence. Several new diagnostic tools have been developed at CEM-UT which aid in the understanding of the physics of the launch package during testing.

Projectile designers carefully inspect the muzzle voltage data from a shot because it best indicates what is happening to a package in-bore. Launch package efficiency can be directly correlated to how and at what velocity the package transitions. Designers are also concerned with what is occurring before the package transitions. Unfortunately, the muzzle voltage prior to transition is about 20 V and cannot be differentiated from noise using old methods of recording muzzle voltage. This concern brought about the development of a new high resolution muzzle voltage method which also greatly reduces the amount of noise on the signal. Since the muzzle voltage is the only source of determining transition time, a new diagnostic tool was developed as an independent method of resolving transition. This tool uses a photo transistor circuit mounted in the breech plate of the gun to record light resulting from the launch sequence. A third diagnostic tool was developed to record the plasma pressure of a transitioned solid armature at the muzzle of the gun. This tool helps determine the magnitude of transition as well

as yield important information for the design of railgun structures. The last piece of instrumentation developed consists of a new trigger method for the flash x-ray system at the muzzle. Muzzle x-rays have become the most important diagnostic tool in determining package integrity and contact wear during the launch. The new trigger system has become the most reliable to date and does not depend on a prior knowledge of test parameters for a trigger. This paper will discuss the development of each of these diagnostic tools and their importance to launch package development.

HIGH RESOLUTION MUZZLE VOLTAGE MEASUREMENTS

The muzzle voltage signal is the most important data recorded for armature designers. Not only is it a directly related to the armature-to-rail interface voltage, but is also used to calculate transition velocity, armature exit times, and muzzle and armature dissipation energy. A typical muzzle voltage signal on 90 mm gun firings starts around 10 to 20 V [1]. As the armature moves through the bore, the contacts begin to heat up and lose material. Once enough material is lost and the electromagnetic force pushing the contacts toward the rails is no longer sufficient to keep the armature in contact with the rails, transition occurs. This can be seen in the muzzle voltage signal as a sharp rise of 100 to 200 V using a solid armature on the 90 mm Task B gun at CEM-UT. Old methods of recording muzzle voltage show the sharp rise in voltage but fail to produce an accurate representation of the signal at low voltages, prior to transition. Accurate muzzle voltage data early in the shot would help the armature designers produce better sliding contact models by allowing separation of the inductive effects, the body drop, and the sliding interface voltage.

In an attempt to improve on the quality of the muzzle voltage data, a new method of measuring muzzle voltage was developed. The method used for years at CEM-UT was to connect a resistor across the rails at the muzzle of the gun and measure the current through the resistor with a Pearson current transformer. The voltage divider was positioned at the muzzle of the gun and a long twisted pair wire was run back to the screen room and recorded on an oscilloscope. Figure 1 shows a typical signal recorded inside the screen room using the old voltage divider. There are two problems to note with this signal. First, the voltage, even on a high resolution scale, is not accurate when the amplitude is small. There are three reasons for this. First, the Pearson coil saturates from the early transients caused by switching the cur-

Manuscript received April 20, 1994.

This work was supported by U.S. Army ARDEC under contract number DAAA21-86-C-0215.

Figure 1. Gun signals taken by old methods on shot #85

rent from the inductors to the gun; second, the oscilloscope does not have enough resolution to accurately portray the voltage at both low amplitudes and peak voltage. The last problem with this signal is the amount of noise coupled into the data. The noise is caused by the long wire running to the recording device being subjected to large stray electromagnetic fields resulting from the inductor currents being switched into the gun.

A new method of measuring muzzle voltage was developed to address all of these problems. To solve the problem of accurate high resolution of a wide amplitude signal at low amplitude, a divider was used to limit the output to peak voltage specification of the amplifier channel. The amplifier could then be set for high resolution without the distortion encountered when operating beyond its input specification. Also, to reduce capacitive coupling of current into the instrumentation lines, the signal must be isolated from building ground. This was done by using a calibrated 1000 to 1 Tektronics probe (and a dedicated oscilloscope powered by a Honda generator located on level 1 of the vertical gun range.) The probe was fixed to the wall on level 2 of the vertical gun range and connected to the muzzle voltage leads through a switch as shown on figure 2. The switch is used so that an ac outlet voltage can be used to confirm wiring integrity and oscilloscope operation. After checkout, the switch is positioned connecting the muzzle to the oscilloscope through the divider circuit. The Tektronics 1000 to 1 probe is calibrated and compensated prior to placing it in the vertical gun range. The probe is then connected to a Nicolet oscilloscope which is powered by a portable Honda generator for isolation from building ground. For the experiment, the oscilloscope is triggered by the fiber optic transmitter receiver pair and is synchronized with the other recording devices located inside the screen room. To trigger the oscilloscope, a 5 V pulse of 7.5 μ s duration is sent to a transmitter located inside the screen room. This transmitter, upon receiving the 5 V pulse, sends a

Figure 2. New method of measuring muzzle voltage

fiber optic pulse through a cable to the receiver located on level 1 of the vertical gun range. The receiver then outputs a 5 V signal which is used to trigger the oscilloscope. This method for triggering the oscilloscope provides an isolation method which best prevents noise from creating a false trigger. After the muzzle voltage waveform is captured on the oscilloscope, it is stored on diskette immediately following the experiment. Then the data is transferred from the diskette to the computer using an oscilloscope inside the screen room. Figure 3 shows the comparison between an isolated and non-isolated muzzle voltage signal. Several interesting observations can be made from this data. The signal has four cycles of a pulsed waveform that directly match the staging times. These are believed to be the voltage drop across the armature inductance caused by the di/dt of switching the 6.5 μ H inductors. These transients have been present on the muzzle voltage signals before, but were thought to be noise from switching. These four cycles have a lower magnitude and are devoid from the high frequency noise seen on muzzle voltage traces on previous tests. This new method produces a signal which accurately depicts the muzzle voltage signal allowing the launch package designers to better understand what is occurring at the armature to rail interface.

PHOTO TRANSISTOR

The technique of recording bore light to evaluate plasma armature behavior has been developed by other researchers [2] and we are now utilizing similar sensors in solid armature experiments. In an effort to provide more data for the understanding how the launch package works inside of the gun, a new circuit was built to record light emitting from the launch sequence inside of the gun bore. This circuit will help to understand how the armature behaves prior to transition as well as being a second means of determining transition time. The circuit mainly consists of a Honeywell SD3443 NPN silicon photo transistor which is installed in the polyethylene plug at the breech of the gun. The photo transistor is basically a light sensor that produces a voltage signal depending on the intensity of the light. It was felt that after transition,

Figure 3. Comparison of muzzle voltage taken by two methods on shot #85

the photo transistor signal would saturate, but that prior to this time there could be some interesting data that may correlate with other shot data to help better understand the events leading up to transition. The transistor is covered by a clear polycarbonate lens that threads into the breech plug and seals the transistor from plasma generated during the shot. Figure 4 shows a photo transistor signal from Task B Shot #82. At that time, it was questioned what the response time was for the transistor. It was then decided to bias the photo transistor to obtain the fastest possible response time. Because the photo transistor was not operating in the active linear range on previous tests, the response time was questionable. Figure 5 shows the photo transistor bias circuit. To determine the response time a strobe light was used. With this circuit, a response time of 7 μ s was obtained. Even after the photo

transistor was biased there was still a question of whether the data seen is real or noise induced due to the fact that the shielded twisted pair cable that carries the signal runs near the breech of the gun. On Task B Shot #87, another biased photo transistor circuit was placed right next to the photo transistor in the breech plug. The only difference is that the glass into which the light enters is covered so that no light can possibly enter the photo transistor. Any signal seen on this channel will be assumed to be noise induced. The covered photo transistor circuit's signal could be subtracted from the light sensing photo transistor circuit yielding the actual light pulse free of noise.

Now that the signal has been correctly biased and the noise has been subtracted out, the data can be analyzed. The problem here is that the light emitting from the launch package is moving away from the photo transistor. Therefore, the relationship of luminous intensity being proportional to the square of the distance of the source [3] must be applied.

Figure 4. Photo transistor data taken on shot #82

Figure 5. Photo transistor bias circuit

From the experimental data, a position curve can be made from the B-dot signals to accurately locate the package throughout the bore. Using the above described relationship, the resulting waveform can be plotted with the muzzle voltage as seen in figure 6. This data was recorded on Task B Shot #88. The normalized intensity signal makes a small increase early in the signal but flattens out. Inspecting the data further, it appears that photo transistor stops seeing light about 5 ms into the shot sequence. It is believed that the debris cloud resulting from armature ablation is blocking the light from the photo transistor. The early results of these tests are encouraging and more work will be done to further improve this circuit.

PLASMA PRESSURE MEASUREMENTS

Another diagnostic tool recently developed at CEM-UT consists of a pressure measuring device which could be used to determine how "hard" of a transition the armature package undergoes. Plasma pressures have been recorded on railgun tests using plasma armatures [4], but no data existed on solid armature tests. The gun used for these measurements was the Task C 30 mm subscale gun. A piezoelectric pressure transducer was mounted at the muzzle of the gun to measure the plasma produced by a transitioned solid armature. The plasma would directly couple to the transducer and thus put the recording device at risk. The only means CEM-UT had for isolating an analog signal from an oscilloscope was an old analog fiber optic link. The calibration procedure for this piece of instrumentation is extremely tedious and gives an error band $\pm 20\%$. For this reason, an opto-isolator circuit was built for electrical isolation of the transducer signal. The QTC model H11V2 linear optocoupler provided peak voltage holdoff of 7,500 V across the chip. This value far exceeds

the 2,500 V muzzle voltage signal seen on previous tests in this gun. The pins were bent outward and the chip was potted in silicon to provide additional isolation. The entire circuit runs on batteries and the supplies for the output of the optocoupler, which is connected to the recording device, and the rest of the circuit are isolated from one another. The circuit used is shown in figure 7 below. It allows for gain and bias adjustments so the input signal can be tailored to operate in the ± 1.5 V linear range of the optocoupler. An additional adjustment was added to the output of the optocoupler providing an offset adjustment so that more sensitive voltage ranges can be used for better resolution. The circuit is calibrated using a triangle wave which spans the entire linear range of the optocoupler.

A piezoelectric pressure transducer was installed on the Task C 30 mm subscale gun to measure the plasma pressure at the muzzle. PCB Piezotronics manufactures the model 108A transducer used for these measurements. It has a 2 μ s rise time and a linear active pressure range up to 80,000 psi. A 0.5 in. hole for installation of the transducer was drilled and tapped in the top insulator 99.5 in. from the breech of the gun (fig. 8). The transducer has an active area of 0.08 in. Factory specifications for calibration were checked by a static calibration test using a Ametek model T-50 dead weight tester up to 5,000 psi. The test confirmed the stated 15,000 psi/V scale factor.

Because the plasma is directly coupled to the pressure transducer, the opto-isolation circuit described above was used to provide isolation from the recording device. Three

Figure 6. Phototransistor data taken on Task B shot #88

Figure 7. Optoisolation circuit developed at CEM-UT

Figure 8. Location of pressure measuring device on 30 mm gun system

separate tests were performed on the 30 mm gun at CEM-UT on which the plasma pressure was measured. All three tests fired armatures developed by the Kaman Sciences/CEM-UT SLEKE design team. Shots #8 and 10 on this gun used the single contact base push design (fig. 9) and shot #9 used the tandem armature contact design (fig. 10).

For a plasma armature, the theoretical pressure is determined by dividing the Lorentz force by the cross sectional area of the bore. These tests were performed using a metal armature which transitions before exiting the gun. After transition, a metal armature becomes a hybrid armature consisting of both metal and plasma. Because a full plasma front is not present on these tests, the measured pressure should be somewhat less than the theoretical calculation for a plasma armature. Depending on the type of armature and the charac-

Figure 9. Package tested on shots #8 and 10

Figure 10. Package tested on shot #9

teristics of its transition, the percentage is thought to be between 60 and 70%. The last test performed on this gun, shot #10, will be used for illustration purposes. Two generators operating at 3,400 rpm and a peak current of 669 kA were discharged into the gun producing a peak gun current of 1.03 MA. Transition occurred at 0.86 ms with a muzzle voltage of 37 V with the armature traveling at 1,705 m/s. At exit, muzzle voltage had increased to 479 V and an armature velocity of 2,111 m/s was observed. Data recorded during this shot is shown in figure 11.

Although the opto-isolator circuit was designed for the plasma pressure measurements, many more uses were found for this versatile piece of equipment. This circuit would allow a resistive divider, the most reliable type of voltage division, to be optically isolated from the recording devices preventing flashovers to ground from damaging expensive equipment. The scale factor for this divider was 50 to 1 and

3901.0797

3901.0796

Figure 11. Shot data for test #10

Table 1. Summary of shots recording pressure data

Shot #	HPG Speed (rpm)	Peak Gun Current (MA)	Transition		Muzzle Voltage (V)	Velocity (m/s)	Muzzle Voltage (V)	Theoretical Pressure (psi)	Recorded Pressure (psi)
			Time (ms)	Velocity (m/s)					
8	2650	0.717	1.71	1868	25	2083	352	9480	6500
9	3000	0.589	1.59	1371	20	1773	82	20400	2000
10	3400	1.030	0.86	1705	37	2111	479	21500	13300

diodes were used to protect the circuit from being overvoltaged. The diodes are connected in such a manner that the voltage output of the divider is clamped at 4.4 V in both directions. The output of the resistive divider is connected to Vin. The ± 4 V setting is used on the 12-bit input channel of the oscilloscope. Combining this setting with the scale factor from the resistive divider and gain adjustment of the operational amplifier yield about 0.5 V resolution. This circuit allows measurements of muzzle voltage prior to transition, typically on the order of 20 V, to have an error band of $\pm 3\%$. Another advantage of this circuit is that offsets associated with the switching transients are non-existent since the divider is purely resistive. To further isolate the system and to reduce noise from ground faults, the oscilloscope was run on a Honda portable generator. The oscilloscope was positioned close to the divider circuit to reduce the length of cable to a minimum. This method provided noise-free data with very good resolution.

Using the measured value of gun current at exit, 655 kA, the theoretical plasma pressure was calculated to be 21,500 psi. The transducer measured the pressure at 13,300 psi (± 400 psi). This value corresponds to 62% of the theoretical value. A summary of the data recorded on these three tests is shown in table 1. The opto-isolation circuit allowed these measurements to be taken without putting the recording device at risk. From this data, it can be seen that as the measured plasma pressure nears the theoretically calculated pressure, the "harder" a transition the armature experiences.

CONTINUOUS WAVE X-RAY TRIGGER SYSTEM

The flash x-ray system used to x-ray the package in flight at the muzzle is the most important diagnostic for the determination of launch package integrity. The x-ray image verifies package integrity immediately after it exits the gun. CEM-UT has gone through a number of methods of getting a reliable trigger for the flash x-ray system [5]. Using a continuous wave (CW) x-ray system for triggering the flash x-ray system is the final step in this evolutionary process. The CW x-ray unit uses two 30 kV power supplies to generate a 60 kV, 20 mA x-ray source. X-rays cross the flight tube in the path of the projectile and strike a scintillator screen coupled to a photo-multiplier tube. The CW x-ray system generates a trigger when an object larger than 0.5 in. wide blocks the x-ray source for at least 10 μ s. This will cause the photo-multiplier tube output voltage to drop to 0 V, which is sensed by a comparator circuit. The comparator circuit then generates a signal for the delay generator to trigger the muzzle x-ray system. The delay generator is set for no delay because the CW

x-ray source is positioned such that the package will be centered lengthwise on the film.

The CW x-ray trigger is far superior to those used in the past. CEM-UT had developed a muzzle voltage comparator circuit that showed about 75% reliability in the past. However, the comparator circuit would not produce a trigger when the package failed in-bore thus dissipating gun current so that no muzzle voltage signal would be present at exit. An armature failure event is an occasion when the muzzle x-ray data is quite valuable. The CW x-ray trigger system solves this problem because it is independent of any diagnostic signal from the railgun test. When the x-ray beam is interrupted by anything opaque, the CW x-ray generates a trigger and whatever is in front of the x-ray head is the image recorded. Since its installation, the CW x-ray system has successfully triggered the flash x-ray system at the muzzle 95% of the time.

CONCLUSIONS

There is an ongoing effort to provide the launch package designers the best quality data so that they can make modifications to their packages and predict what will happen on the next test. The new diagnostic tools reported in this paper are a step in the direction of measuring the physical characteristics of a launch package during a railgun test. Most of the work will be concentrated on recording data up to transition with the best possible resolution. This will help designers understand what steps need to be taken to increase the time to transition and thus increase efficiency of their launch packages.

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