X-RAY DIAGNOSTICS FOR THE SINGLE SHOT LABORATORY GUN

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X-Ray Diagnostics for the Single Shot Laboratory Gun

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ABSTRACT—The projectile packages being fired out of the 90-mm Single Shot Gun at the Center for Electromechanics at University of Texas at Austin (CEM-UT) have evolved into designs consisting of rods capable of penetrating armor. Throughout the evolution of these penetrating projectiles, high-speed flash x-rays of the package in flight have proven invaluable in determining the integrity of the entire launch package. The flash x-ray system installed in the vertical gun range at CEM-UT consists of two pairs of orthogonal view x-ray heads and a single head station. One pair, located at the muzzle, of the gun is used to verify package integrity as the projectile exits the gun. The other pair is located in the target chamber at the bottom of the vertical gun range and used to determine the projectile entry angle. The single head will be located below the target and used to determine the debris pattern associated with the penetration. The two pairs of x-rays are very useful in determining an accurate velocity of the projectile. Data from both the muzzle and target x-ray systems as well as the method to reliably trigger these systems will be presented.

INTRODUCTION

As the technology advances in the area of electromagnetic launchers, the amount of energy being supplied to a launch package will increase. Upon attaining levels of performance not previously reached, needing to know the integrity of the launch package becomes more important. The most useful piece of diagnostic equipment to verify package integrity is a flash x-ray system. A reliable method to trigger the x-rays at the exact instant required to capture the image on x-ray film is essential. Also, if the technology is to advance in the area of delivering penetrating rods to a target, methods to analyze impact and resulting debris patterns must be available. The flash x-ray is the best diagnostic tool for such analysis.

A flash x-ray system capable of performing the functions discussed above is in place and being used as an important diagnostic tool in the vertical gun range at CEM-UT. The x-ray system at CEM-UT has the capability to capture orthogonal view images at the muzzle of the gun. The x-rays from the muzzle of the gun are used to analyze package integrity after exit. A second set of orthogonal x-ray heads have been positioned 1 m above the target, producing images which can be used to determine the entry angle and position of the penetrator prior target impact. Another x-ray head will

be placed below the target for the purpose of analyzing the debris pattern resulting from penetrator impact with the target. Noise-immune trigger circuits have been designed, tested, and proven to operate successfully in the harsh electromagnetic environment.

This paper will present the x-ray setup used at CEM-UT. Included are methods to reliably trigger the x-rays and techniques to protect equipment from the dangerous environment in the target area. Also included will be results from tests performed in the vertical gun range.

X-RAY EQUIPMENT OVERVIEW

The flash x-ray system used at CEM-UT consists of a 300 kV Scandiflash system [1]. The Scandiflash system includes a main control console containing a 50 kV power supply, ion pump power supplies for each x-ray head, pressure control units for the freon and dry air needed for system operation, and a delay generator to trigger each pulser. Also, each station has a pulser used to generate the necessary voltage used to produce the x-ray. The voltage pulse is carried to each head from the pulser by a 300 kV coaxial extension cable. Each head has an ion pump to keep a vacuum on the head. A typical setup is shown in Fig. 1.

The x-ray system is used in the following sequence. The freon and dry air pressures must be set to the proper levels using the pressure control units. The power supply control unit allows the user to adjust the high voltage supplied to the pulser for varying x-ray intensity levels. After the intensity level is determined by the user, the power supply charges the pulser. The pulser consists of several capacitors which are charged in parallel but discharged in series in order to step up the voltage. The capacitors are switched from a parallel to series configuration by the use of spark gaps. Once the pulsers have been charged, the system awaits a trigger. Upon receiving a trigger input, the delay generators output a pulse to the trigger amplifier on the pulsers once the preset delay time has been reached. The trigger amplifiers generate a 12 kV pulse used to trigger the spark gaps. The output of the pulser is used to create the x-ray pulse in the cold cathode flash x-ray tube. The image is captured on Dupont NDT-89 film with increased intensity provided by the Dupont NDT-9 salt screens.

Fig. 2. Schematic of muzzle voltage comparator trigger circuit

Large voltage spikes occur as a result of switching. To prevent these switching transients from triggering the x-rays early, the comparator circuit is enabled after the switching sequence is complete. Once the circuit receives the enable signal through its fiber optic receiver, the comparator starts tracking the muzzle voltage. A 500:1 voltage divider is used to provide the muzzle voltage input signal. The circuit includes dual complimentary comparators. One comparator is set for a positive voltage and the other is set for the same voltage inverted. The dual comparator circuit is used because it makes the polarity of the muzzle voltage signal noncritical. Once the muzzle voltage has reached the preset level, the comparator triggers a one-shot chip which outputs a 100- μ s pulse. This pulse is amplified by a dual complimentary J-FET pair and transmitted fiber optically to the delay generator responsible for triggering the pulser. This method works well when the projectile exits in one piece. However, when the projectile is in pieces, there is not a well defined armature current concentration and a sharp rise in muzzle voltage does not occur. Any trigger scheme has trouble recognizing the largest piece of a broken launch package. For this reason, the high-speed cameras which frame continuously over the launch interval are used to diagnose failed tests.

Many x-ray trigger methods have been tried at CEM-UT. the most reliable method is the muzzle voltage comparator circuit described above. The other trigger schemes investigated and the reason for not using each method are shown in Table I. Of the methods listed, only the continuous wave x-ray method works adequately with solid projectiles. However, the continuous wave x-ray machine creates a hazardous radiation area and must be positioned so that it will not expose the x-ray film. All of the methods contain electronics which must be made to withstand the noisy electromagnetic pulse environment of the railgun. Using

battery power supplies and fiber optic cables greatly reduce circuit susceptibility to noise. Experience using the trigger methods listed in Table I helped in the creation and design of the muzzle voltage comparator trigger circuit.

TABLE I. METHODS OF X-RAY TRIGGERING

Trigger Scheme	Reason for Failure
Fiber optic break wire	High speed air column preceding package causes rupture of screen
Make screen	At muzzle, high speed air column preceding package causes early screen breakage
Break screen	High impedance compared to electrical noise. Hard to maintain continuity with screen
Coil of wire encircling flight path	Difficult to determine actual position of package. Very susceptible to noise
B-dot	Difficult to determine position of package because of changing current distribution in armature. Very susceptible to noise
Continuous wave x-ray	Signal to noise ratio low for nonmetallic packages. Associated electronics are susceptible to noise. Hazardous environment because of x-radiation

TARGET X-RAY STATION

The two orthogonal view x-ray heads above the target are protected by large, thick steel boxes approximately 21 in. x 31 in. x 17 in. The boxes are made of 1 in. thick mild steel to protect the heads from the blast and the flying debris. As seen in Fig. 3, the x-ray pulse is directed through a hole in the corner of the box. By positioning the box in this manner, flying debris strikes the box at an angle making it more easily deflected. The heads are protected at the corner access holes by 2, 0.5 in. thick pieces of Lexan™ inside the box. The

Fig. 3. Overhead view of target x-ray station

protection box design was calculated to take a 300 psi overpressure from any direction and remain intact and mounted to the target chamber wall. The single view below target x-ray head will be protected in a box very similar to the above target heads.

The above-target film holders are 17 in. wide by 61 in. tall and 60 in. from their respective x-ray heads. This film size will accommodate an x-ray area 35 in. tall x 10 in. wide at the center of the flight tube. A series of nonmetallic materials are used to protect the film from the blast and debris. A piece of Kevlar™, a 1 in. thick high density polyethylene plate, and two pieces of 0.5 in. Lexan™ are used in front of the film. One of the 0.5 in. Lexan™ pieces has a lead grid attached to it. An exposure test was done to observe the attenuation level due to these materials being in front of the film. Image intensity and detail were not significantly affected with this protection scheme. These film holders have performed very well in the harsh target chamber environment during railgun tests. No lost or damaged film due to flying debris or blast pressure has occurred.

The target x-rays are triggered using a foil make screen trigger circuit shown in Fig. 4. The make screen consists of two pieces of aluminum foil mounted to either side of a moderately thick piece of plastic. The plastic is mounted with clamps to a rectangular shaped structure made of half-inch conduit. The structure is placed on top of the x-ray film protection boxes just below the bottom of the flight tube. Each piece of aluminum is connected to an electrode which supplies a variable dc voltage. A 2.5 kV, 10 mA supply charges the make screen. When the projectile breaks the screen, the two pieces of aluminum foil short creating a negative-edge voltage spike. When the short occurs, the Pearson current transformer senses the current and its output,

Fig. 4. Schematic of make screen trigger circuit

terminated by a 50 Ω resistor, generates a trigger, which is converted to a fiber optic signal, and input to the delay generator. The delay generator outputs the trigger signal to the pulser after a preset time has elapsed. The delay time is calculated by dividing the distance from the make screen to the middle of the film by the simulated velocity for the shot. The shorted make screen also discharges a capacitor creating a voltage spike. This pulse goes through a 1,000:1 voltage division and is input to a operational amplifier. The noninverting operational amplifier circuit output is isolated by an optocoupler. The optocoupler output has trimpots for the gain and offset used to linearize the signal. The output of this signal is collected to be used as a data point for calculating velocity.

The foil make screen circuit is a more reliable trigger method than the comparator circuit used at the muzzle. However, using a make screen at the muzzle would present other problems. Very large overpressures precede the package in the gun and would likely cause the make screen to rupture and trigger early. Another problem is the space constraints at the muzzle of the gun. There is no room to place the screen and not partially block the film. Furthermore, it would be hard to shield the make screen circuit from noise encountered at the muzzle of the gun. For these reasons, it was decided to build the comparator circuit described above.

USING THE X-RAYS TO DETERMINE PACKAGE VELOCITIES

Because velocity is so critical to a railgun shot, it is important to accurately measure this value. The flash x-ray system allows for easy and accurate calculation of in-flight velocity. The distance the projectile traveled between the two x-rays stations must be calculated. This is done by using the measured distance to the center of the film and adding or subtracting the offset from the developed x-ray film. Parallax correction calculations must be made to determine the true velocity from the apparent velocity on the film. The affects of parallax are shown in Fig. 5, where the black object appears to be moving faster than the white object. Once the parallax correction calculations are made, the true velocity can be determined.

Fig. 5. Effects of parallax

The velocity calculation consists of a few simple steps. After parallax corrections are made, the actual distance traveled can be determined. The position of the package is measured from the centerline of the film for both the muzzle and target x-rays. The distance from the muzzle of the gun to the centerline of the film was accurately measured using a surveyor's tape. The difference in distance from the muzzle to the package for the two x-ray stations is then divided by the elapsed time between the two x-ray pulses. The x-ray pulse times are recorded on a digitizer. The recorded signal is generated by the pulser and consists of a short 120 V spike which triggers a one-shot chip, used to lengthen the pulse. The velocity calculation for shot #52 will be used as an example. After correcting for parallax, the package was measured 13.6 in. from the gun muzzle by the muzzle x-rays and 1,332.6 in. from the muzzle by the target x-rays. Therefore, the total distance traveled by the package was 1,319 in. From the recorded data, the difference in time between the two pulses was measured at 24.1 ms. Using this time and converting into mks units, the error calculation yields:

$$\begin{aligned} v &= 33.5 \text{ m} / 24.1 \text{ ms} \\ &= 1,390 \text{ m/s} \end{aligned}$$

The error band for this calculation is found using the equation:

$$\text{error} = \partial x / \Delta t + (\partial t / \Delta t) v$$

The position of the package can be measured within an inch at both x-ray stations. And the time can be recorded within one digitizer time interval for each x-ray pulse time. Therefore, using the elapsed time of 24.1 ms and converting into mks units yields:

$$\begin{aligned} \text{error} &= (0.051 / 0.0241) + (32e-6 / 0.0241) 1,390 \\ &= 4 \text{ m/s} \end{aligned}$$

Hence, the error band for this example is $1,390 \text{ m/s} \pm 4 \text{ m/s}$. The velocity from the x-ray film agrees with the exit velocity from the shot as measured by b-dots, 1,381 m/s. The velocity calculated from the x-ray film is more accurate than the b-dot velocity for several reasons. First, the b-dots measure the

velocity over the last 0.5 m of the gun while the package is still accelerating, whereas the x-rays measure the velocity after exit. Secondly, the distance between the x-rays is much much greater than the distance between the b-dots (33.4 to 0.5 m), which dramatically reduces error. Finally, the current distribution in the armature changes as the packages moves down the gun, making it impossible to record the time of the same point on the armature from the b-dot crossings. The only error from the x-ray velocity calculations result from the accuracy of measurements of position and time. The effects of atmospheric drag at these velocities and gravity at this distance are negligible. For these reasons, the velocity calculated using the x-ray film is the most accurate velocity measurement used at CEM-UT.

DETERMINING ENTRY ANGLE OF PENETRATOR INTO TARGET

Another important function of the x-ray system is the determination of the angle at which the penetrator enters the target. The above target x-rays record orthogonal images one meter above the target. From the orthogonal views, an accurate map can be made of the position of the package prior to impacting the target. From this map, the distances from the ends of the projectile to the grid can be measured. Using these distances and some simple trigonometry, the entry angle can be determined. For accurate measurements of the entry angle, grid alignment is critical. The grid is carefully aligned to the film holder fixtures prior to each shot. The fixtures were accurately positioned using a level upon installation. The angle measured from the film can be used to approximate the actual entry angle. The projectile designers are very interested in the angle at which the penetrator enters the target for performance analysis.

BELOW TARGET X-RAY STATION

Upon the installation of the below target x-ray station, the x-ray system at CEM-UT will be complete. This x-ray station will consist of a single head and pulser. The head and film will be protected from flying debris using the same scheme as the above target x-ray equipment. The single view x-ray head will be used to map the debris pattern associated with penetration of the target. The pulser will be triggered using a foil make screen circuit mounted on the bottom of the target. The head will be located 58 in. from the center of the flight tube and allows for a 16 x 16 in. window to be captured. Once installed, the below target x-ray station will assist the projectile designers in their analysis of the penetrator performance.

RESULTS OF TESTS PERFORMED AT CEM-UT

At the inception of the single shot gun project and for the first year and a half, an outside contractor was responsible for x-ray diagnostics. Since the personnel at CEM-UT have taken over x-ray diagnostics for the last two years, the x-ray system has gone through many modifications to optimize

performance. Since the current trigger system has been in place, muzzle x-rays have been successfully recorded 76% of the time. Fig. 6 shows a muzzle x-ray taken of a two-piece C-shaped armature with a threaded rod launched on shot #45. The target x-ray system has shown a 77% success rate since current trigger systems have been installed. Fig. 7 shows a target x-ray of the rod 1 m prior to penetration on shot #45. X-ray pictures such as these have greatly assisted in the analysis of projectile performance. The x-ray system can also show projectile failures. Fig. 8 shows the tip broken off of a rod from a Kaman Science UHVP projectile package. This package was launched on shot #24. Fig. 9 shows

muzzle x-rays of two very similar Kaman Science UHVP packages from shots #25 and #34. The nose of the dart from shot #25 is obviously broken as compared to the intact dart of shot #34. Such failures do not appear in the data acquisition diagnostics and are not always discernable on the high-speed film. It should now be clear why a reliable flash x-ray system is an invaluable diagnostic tool for electromagnetic launchers.

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REFERENCES

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Fig. 6. Muzzle x-ray of package from shot #45

Fig. 7. Target x-ray of rod from shot #45

Fig. 8. Broken dart from shot #24

Fig. 9. Comparison of UHVP packages from shots #25 and #34