AN INTERFEROMETRIC MEASUREMENT TECHNIQUE FOR RAILGUN STRUCTURES

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Abstract: A technique to measure the dynamic expansion of a railgun bore under conditions of high magnetic stress has been developed. In this procedure bore deflections are detected by a Michelson interferometer apparatus. The measurement is made during application of a current pulse which produces deflections similar to those in an actual projectile launch. The technique has been successfully used with three different "barrel" configurations whose rails are electrically connected outside the bore at the muzzle. These configurations were: a parallel plate bench model, a simple railgun, and an augmented railgun. Even with the application of relatively modest current, bore deflections were readily measured. For these low current tests, the deflections scaled as the square of the current indicating that the forces were within the structures' elastic limits.

Introduction

In a system designed to convert stored electrical energy to the energy of mechanical motion one will produce large forces on the structure in addition to the desired accelerating forces. The problem of deflections of current carrying conductors and the effects on busbar supports has been studied in the power utility industry[1] and, more recently in the development of electromagnetic (EM) launchers[2,3,4]. The problem with busbars in the utility industry is aggravated by natural frequencies of a few hundred hertz so that mechanical resonance may be possible. During operation, electromagnetic launchers must cope with even higher transient currents than the utility industry must contend with under short circuit fault conditions. With the anticipated use of sequential pulsers (eg., Compulsators or other pulsed power supplies designed for high rate of fire) the EM gun designers may also have to contend with resonance. In any of these cases, the inadequacy of support structures under transient magnetic forces can lead to degraded performance or catastrophic failure. A study of the structural behavior of a mechanical system can assist in preventing failure as well as optimizing the design for a given performance. In developing railguns as efficient, long life devices, an understanding of material deformation under pulse loading is necessary. The bore's dimensional integrity is important for both the armature and the projectile as they travel the length of the rail pair. Deformations may affect not only in-bore conditions such as friction, balloting, and launch attitude, but also armature function; the fit of the armature to the bore is critical since the armature must complete the rail to rail circuit by maintaining two, high current, sliding electrical contacts. Bore expansion is a very important factor for the control of plasma armatures and maintaining the contact forces in solid armatures.

The railgun type of electromagnetic launcher has been widely studied. The essential features of the railgun are shown in Figure 1. In the simplest form of the device, current is applied to a normally stationary, parallel pair of conducting rails. A conductor, either solid or gaseous, free to slide between the rail pair, completes the circuit and also carries the same current. The moving conducting element is called the armature. The interaction between the current and its magnetic field produces a force tending to expand the current carrying loop; this leads, of course, to acceleration of the armature. Unfortunately, the same interaction which produces projectile acceleration also produces a transient, bore distorting, replusive force between the rails.

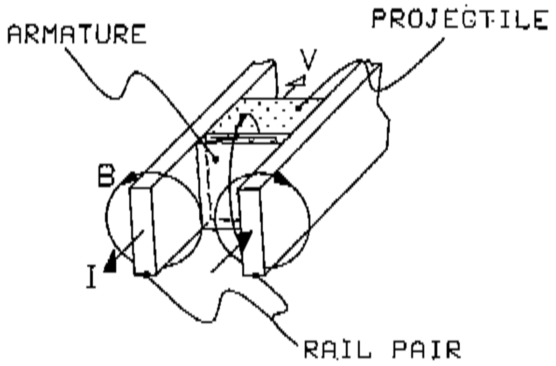

Figure 1. Schematic illustration of a railgun.

Interferometry is a technique which is used to measure change in displacement of an object. Figure 2 is a schematic of a simple laser interferometer which shows the process of splitting a beam of coherent, monochromatic light into two beams.

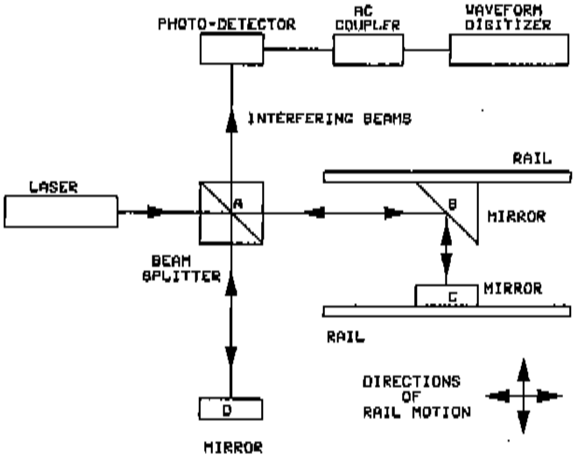

Figure 2. Laser interferometer arrangement.

Beam A-D, the reference beam, never changes in length; beam A-B-C, the object beam, is reflected by the objects that will be moving (the rail pair). Both beams are reflected back on themselves and recombine at the splitter. A phase difference between the two path lengths may produce either constructive or destructive interference of the beams. As the path length of the object beam changes the alternate constructive and destructive interference produces a sequence of light and dark fringes. Since the fringes result from phase difference in light of known wavelength, a relationship between the number of fringes and movement of the object may be determined. In dynamic tests, an oscilloscope records the time-varying output of a simple photodetector which senses the varying light intensity as fringes are produced.

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From this record the actual change in rail separation versus time may be determined. High speed, long record length recording equipment is required for very high current tests. This requirement stems from the sensitivity of the technique which detects displacements on the order of one-half the wavelength of the light source.

In the work reported here, four sets of bore deflection experiments were performed. The first consisted of a rudimentary conducting parallel aluminum rail pair, pulsed with currents less than 5,000 amperes. The second set of experiments involved a 1/4" square bore augmented gun rated for 150 kA, and built by BRL. The main supporting side walls are constructed from G-11, and held in place with bolts. The final sets of tests were performed on two short electromagnetic railgun barrel sections; 15mm and 50mm square bores designed and built by IAP Research Inc[5]. The 15mm structure is rated for 400 kA while the larger is rated for 1.5 MA. For the latter three sets of experiments, maximum currents were on the order of 100,000 amperes.

Interferometer Arrangement

The interferometric components and their arrangement employed in both the aluminum rail pair and all the barrel experiments are as shown in Figure 2. The railgun bore with its muzzle shorted does more than simply expand. Axial growth also occurs as magnetic forces tend to drive the shorting bar forward. To determine how many fringes pass in front of the detector for a given change in rail pair position, let us assume that each mirror moves a distance of $\delta/2$, and translates towards the beam splitter by an amount ε. These motions are shown in Figure 3.

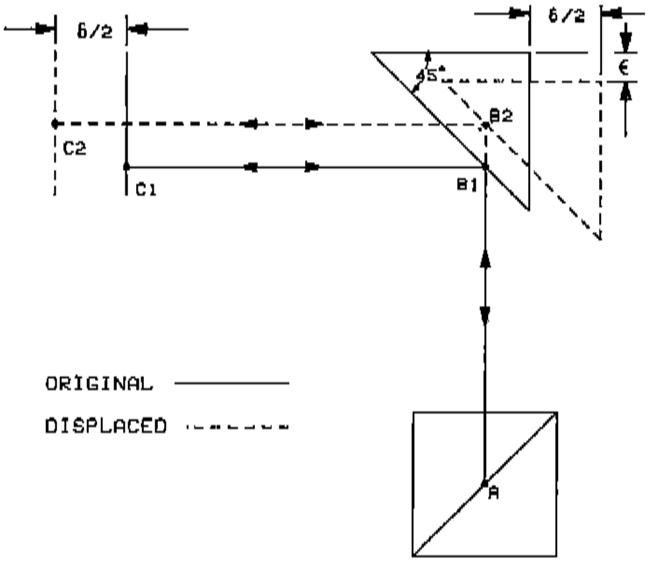

Figure 3. Optical path length changes for two dimensional mirror motions.

The original optical path is A-B1-C1-B1-A and the displaced path is A-B2-C2-B2-A. It can be seen that the total displaced path A-B2-C2-B2-A is longer than the original path A-B1-C1-B1-A by an amount equal to $2(\delta - \varepsilon)$. The number of fringes passing the detector is $2(\delta - \varepsilon)/\lambda$, where λ is the laser wavelength. Therefore the number of voltage waveform cycles in time on the oscilloscope is proportional to the rail pair separation change in time and is given by:

$$\delta\ (t) = N_{bg}(t) * \lambda / 2 + \varepsilon\ (t) \qquad (1)$$

where $N_{bg}(t)$ is the number of detected peaks occurring in unit time. The displacement ε can easily be measured under the same load conditions and at the same rail location, by mounting a mirror perpendicular to the rail surface. The axial growth is then:

$$\varepsilon\ (t) = N_{ag}(t) * \lambda / 2 \qquad (2)$$

where $N_{ag}(t)$ is the number of detected peaks occuring in unit time. The corrected bore expansion is given by:

$$\delta\ (t) = (N_{bg}(t) + N_{ag}(t)) * \lambda / 2 \qquad (3)$$

Experiment: Electrical and Mechanical

The pulser used in these experiments is described in detail elsewhere[6]. It is capable of delivering maximum currents of 120 kA, in a 1/2 cycle time of 850 microseconds.

A Rogowski coil was used to measure the time rate of change of current flowing in the circuit. The optical fringe detector consisted of a RCA hybrid silicon photodiode with integral preamplifier module. The output of the circuit was fed into a capacitive AC coupler with a 50-ohm terminator. The data was collected using a Nicolet 4094 oscilloscope. A typical detector output trace taken on the aluminum rail pair is shown in Figure 4. The actual displacement is obtained by simply counting the number of sinusoidal peaks. Peak deflection (near zero rail velocity) occurs when a low signal amplitude is concurrent with a low output frequency. This can be seen at 868 µs. For this particular experiment, 29 fringes are detected, corresponding to a peak expansion of 9.17 micrometers (.00036 in.). Maximum velocity is the point where the sinusoidal output frequency of the detector is the highest. This occurs at 429 µs. The peak velocity is approximately 21 mm/s.

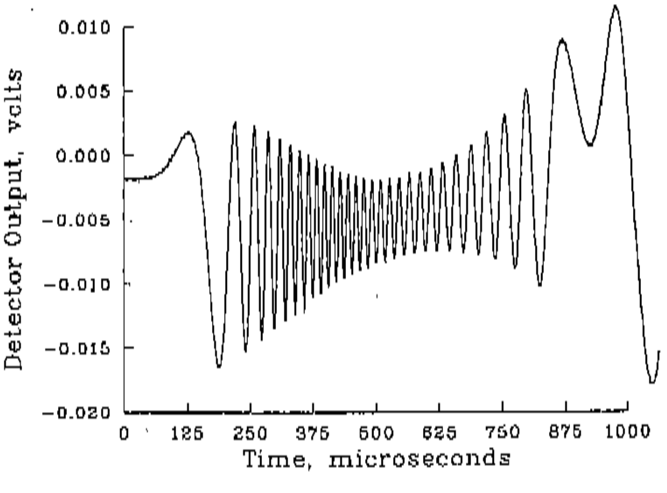

Figure 4. Typical detector output.

The experimental setup for the rudimentary aluminum rail pair is shown in Figure 5. The aluminum rails are 2.3 mm (0.09 in.) thick, 190 mm (7.5 in.) long and 38.1 mm (1.5 in.) high with a nominal rail-to-rail separation distance of 25.4 mm (1 in.). Only the breech and muzzle ends of the rails are anchored to fiberglass/epoxy laminate (G-11) supports. At the breech a 5/8-inch bolt into a copper block is used to connect the current leads (12 gage wire) from the power supply to the rails. Since no projectiles were used, the rails were shorted at the muzzle using two 3/8-inch steel bolts. The flat mirror, C, is mounted to one rail with double sided tape while the other mirror, B, is held at a 45 degree angle by a plexiglass mount attached to the other rail in the same manner. Both mirrors were located at the axial and tranverse dimensional centers of the rails.

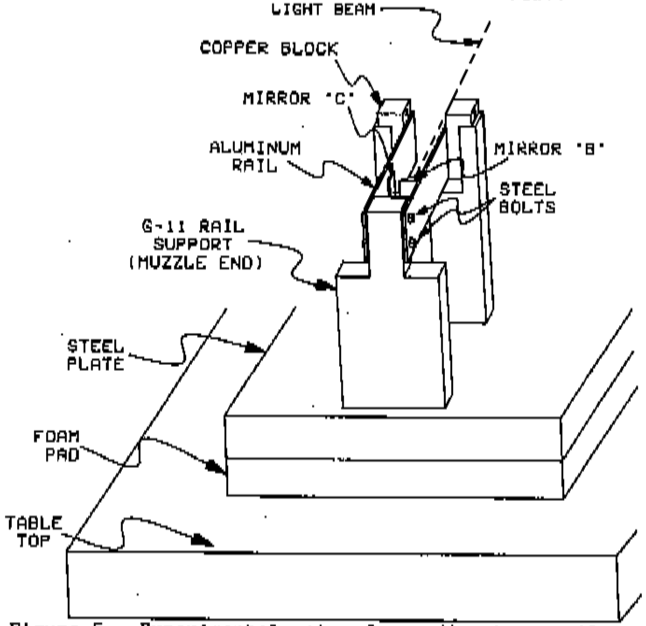

Figure 5. Experimental setup for rudimentary rail pair replusion measurement.

The 1/4" augmented barrel experiments were set up in much the same way except that the mirrors were located 6" in from the muzzle end of the 24" long rails. The mirrors were positioned midway between two bolts of the containment structure. In addition to those for inside measurements on the bore, a mirror was fixed on the outside of the G-11 containment structure, opposite the inside measurement location. This mirror was used in another interferometric measurement of the outside structure expansion during a current pulse. Both sets of deflection measurements were performed under various mechanical load conditions and peak currents.

For the two, short barrel-section experiments the interferometer was setup in a similar fashion. However, for both barrels, the bore measurements were made at two different axial locations. Also, mirrors were mounted perpendicular to the rail surface to measure the axial displacement of the rail which occurs when the muzzle short is driven by the Lorentz force. Again, measurements were made at various mechanical loads and peak currents.

Optical and Mechanical Considerations

Several factors were considered in the optical equipment setup. First, the optical path difference between reference and object beams must be within the coherence length of the laser. Since this length was unknown, the problem was circumvented by making the path lengths nearly equal.

A second consideration was the system's sensitivity. Because the interferometer will measure displacements smaller than an optical wavelength, extremely small vibrations result in fringes passing the detector. To avoid these small vibrations the apparatus was assembled on a massive teflon plate isolated by mounts of low stiffness. Thus, only low amplitude, low frequency vibrations were transferred to the equipment. The movement of the rails during a current pulse produced temporal changes in the interference pattern which are significantly higher in frequency than those produced by external vibrations within the test area.

To avoid unwanted interference patterns that occur when the beam is reflected back on itself at the unsilvered interfaces of the beam splitter, the splitter was tilted slightly, requiring mirror "D" to be moved for compensation. Now the two paths A-D and A-B in Figure 2 become non-perpendicular and secondary interference patterns do not appear where the detector is located. Secondary reflections at the flat mirrors were eliminated by the use of front-surface silvered mirrors.

The above considerations were generally easy to compensate for and did not significantly hinder the experiment once the initial setup was refined.

A. Aluminum Rail Pair

A similar experiment was performed previously[7] with a single crowbarred capacitor which provided an exponentially decaying current pulse. The bore expansions obtained from past tests agree with more recent testing using a half cycle sine wave current pulse. The bore expansions obtained are plotted as a function of time in the lower portion of Figure 6. For comparison the bore expansions measured previously are also plotted. The upper portion of Figure 6 shows a current pulse from each experiment.

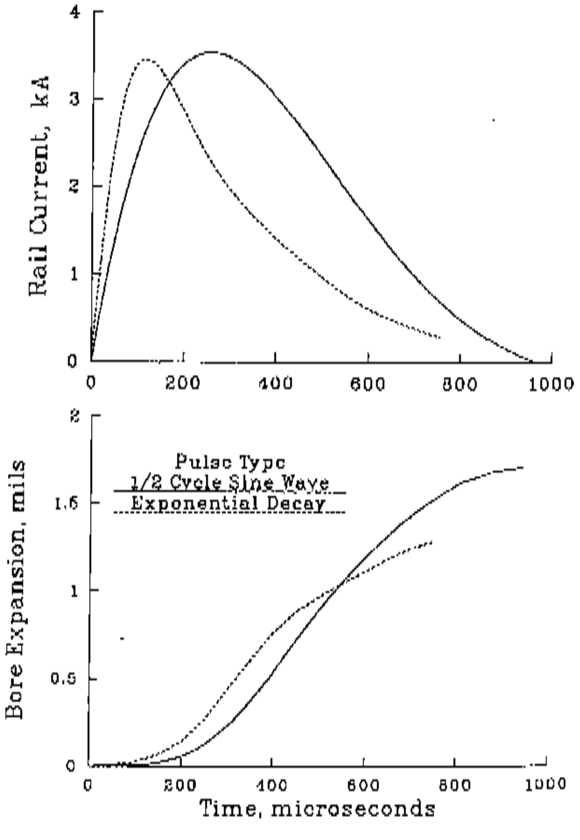

Figure 6. Rail current and bore expansion versus time.

Since this measurement includes both the bore growth as well as any axial displacement of the mirrors a second measurement was performed. A mirror was mounted perpendicular to the aluminum rail surface at the same location. The measured axial growth was only 4 - 5 % of the bore growth measured.

B. 1/4" Augmented Gun

A photograph of the augmented gun and its experimental setup is shown in Figure 7. The mirror for the outside measurement can be seen between the 5th and 6th bolt in the picture. Because of the size of the bore, it was difficult to mount the mirrors in the bore and still obtain a return beam at the beam splitter. A distance of 6 inches in from the muzzle yielded acceptable results and located the mirrors between two bolt pairs. The muzzle short relied on a frictional fit between the rails and the copper blocks to obtain good electrical contact. It is not known how much the copper rails stretch in the axial direction with this type of connection.

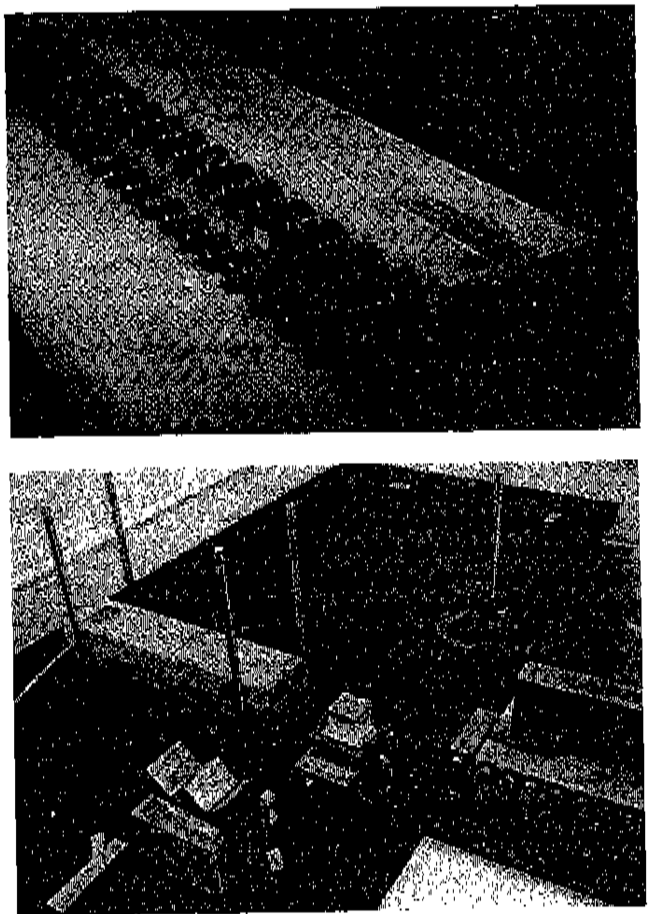

Figure 7. Photographs of augmented railgun and interferometer arrangement.

Initial tests were performed with a prototype of the four module power supply. The half cycle time of the current pulse was changed from 800 microseconds to 1 millisecond and the bore deflection was found to be insensitive to the pulse width change. The top portion of Figure 8 shows two typical current pulses obtained with one module. To check the mirror's position relative to the center line between the bolts, one pair of bolts was removed adjacent to the muzzle end of the mirrors and the gun was pulsed. Then the bolt pair was replaced and the bolt pair adjacent to the breech end of the mirrors was removed and the gun was re-pulsed. There was no difference in the number of fringes obtained. Since the 1/4" guns' containment structure was of the bolted type, only three bolt pairs per mirror side (BP/MS) were varied in torque. All remaining bolts were kept fixed at 56.3 N-m (500 in.-lb). This was done for various initial charge energies. The results for the inside and outside measurements of deflection are plotted versus different peak currents for two different torques in the lower portion of Figure 8. In this figure the displacement of one rail has been assumed to be one half of the measured bore expansion.

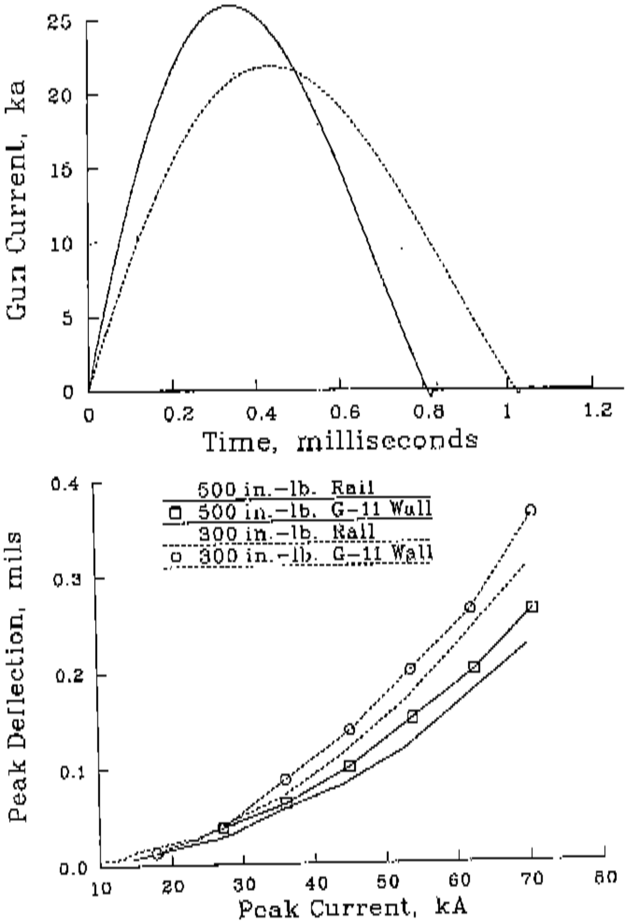

Figure 8. Typical current waveforms vs. time and deflection vs. current for 1/4 inch augmented railgun.

C. IAP Barrel Tests

The configurations tested here were typical square bore railgun cores but with a high stiffness, laminated metallic containment structure. Calculations by the designers[5] predict a bore expansion of 127 micrometers (.005 in.) at rated current for the 15mm barrel and 254 micrometers (.010 in.) at rated current for the 50mm barrel. The mirrors for both bore growth and axial growth measurements were mounted in the bore at two different locations. The 'fit' of the 50mm core assembly to the containment structure was less than design specification and therefore yielded larger deflections than predicted. A summary of the results from the 15mm barrel is tabulated in Table 1. The table includes both bore and axial growth measurements made at two different axial locations; 5.5 and 11 inches in from the muzzle end of the rails.

The results for the 50mm barrel tests are tabulated in Table 2.

Table 1. IAP 15mm Barrel @ 600 in-lb.

Peak Current (kA)	5.5" from Rail End		Corrected B.G. (μm)		11" from Rail End	
	B.G. (μm)	A.G. (μm)			B.G. (μm)	A.G. (μm)
50.0	0.95	.316	1.26	1.26	1.26	0
62.5	1.58	.316	1.89	*	*	0
75.0	2.21	.316	2.53	2.84	2.84	0
87.5	2.84	.632	3.48	*	*	*
100.0	3.79	.949	4.74	4.43	4.11	.316
112.5	4.43	.949	5.37	5.37	5.06	.316

* = Data Not Taken.
B.G. = Bore Growth.
A.G. = Axial Growth.

Table 2. IAP 50mm Barrel @ 1200 in-lb.

Bore Growth Measured @ 11" from Rail End.
Axial Growth Measured @ 7.5" from Rail End.

Peak Current (kA)	B.G. (μm)	A.G. (μm)	Corrected Bore Growth (μm)
50	1.26	.316	1.58
75	2.53	.632	3.16
100	4.11	.949	5.06

B.G. = Bore Growth.
A.G. = Axial Growth.

Bore growth measurements were made at 11 inches in from the muzzle end of the rails while axial growth measurements were made at 7.5 inches in from the muzzle end of the rail. Since the core assembly was not at the design specification, further measurements were not pursued. The upper and lower portions of Figure 9 show typical interferometer detector outputs for the bore growth and axial growth measurement on the 15mm barrel, respectively. The reduced fringe detector signal amplitude concurrent with the lower signal frequency is representative of peak deflection and near zero rail velocity. This condition occurs on the bore growth measurement data at 223 microseconds. The velocity of the rails is directly related to the instantaneous frequency of the output signal. Maximum velocity was reached near 97 microseconds. Peak current occurs at 390 microseconds. The peak axial growth does not occur at peak current nor at peak bore expansion.

There are two sources of error to be considered in this last experiment. To simplify data analysis, the peak current was scaled as the initial charge voltage on the bank. This approximation gave the peak current to within 2 kA for all values which were cross checked. Secondly, the bore growth measurements and axial growth measurements were not performed at the same time. However, assembly differences from test to test were made as small as possible.

Results

In the aluminum rail experiment, the single-module capacitor current was limited to less than 5,000 amperes. There was no containment structure to keep the aluminum rail pair from deflecting. In this configuration it was found that measurable deflections occured even with very low currents. Without containment, peak deflection occurs long after peak current.

The 1/4" augmented gun proved difficult to measure due to the small scale of the barrel and lack of precision optical equipment. Also, there was no correction made for the axial growth of the rails.

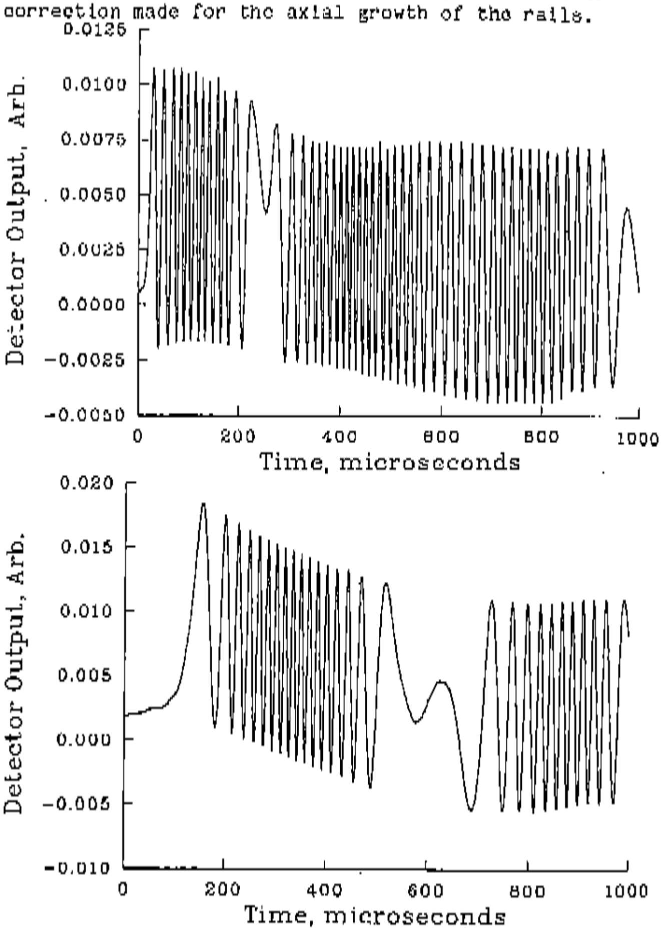

Figure 9. Interferometer detector output for bore growth (upper) and axial motion (lower) on the 15 mm IAP barrel.

Nonetheless, the outside G-11 containment structure deflection measurement should be insensitive to axial growth, and represents an upper bound of deflection measured at the rail surface. At rated current, there will be 52.3 micrometers (.002 in.) of bore expansion. This result is being used as a design criterion for our solid armatures.

The IAP short barrel sections required currents greater than 25 kA to produce detectable deflections. In both of these very stiff structures it was found that the contribution due to axial growth was 25% of the measured bore growth. This was corroborated from the measurements made at two axial locations. The measured peak deflection for the 15mm barrel, scaled to the design current of 400 kA, is 68 micrometers (.0027 in.), 46% less than the predicted value.

In the aluminum rail pair experiment the rails have moved less than 10% of their peak deflection at peak current whereas the augmented gun and short barrel-section rails have moved 95% of their final deflection at peak current. Maximum current was 3,600 amperes in the aluminum rail experiment, 70,000 amperes in the augmented gun, and 112,000 amperes in the IAP barrel tests. The corresponding maximum bore expansions obtained were 43.6 micrometers (.0017 in.), 11.4 micrometers (.00044 in.) , and 5.37 micrometers

(.00021 in.). In all experiments the bore deflections scale as the square of the current.

Conclusion

The laser interferometric technique has proven useful in making small, dynamic deflection measurements in systems under large electrical and mechanical stress. The interference signal pattern was easily transmitted to the detector from the railgun structures. In areas of high electrical noise, a fiber optic cable can be used to transmit the optical signal even further from the apparatus being tested. Two drawbacks to this technique become evident when recording and analyzing the data. First, for large deflections a trade-off has to be made between the sampling rate and the window width of the oscilloscope. Second, with this technique the interferometer measures separation change without indicating whether the rails have expanded, contracted, or translated. This produces some ambiguity in the data reduction if the initial direction of rail motion is not known. Other factors do, however, reduce the ambiguity. The maximum rail separation occurs when the waveform becomes reduced in both frequency and amplitude. When no rail motion is occurring only system vibrations are observed by the detector and these appear as slight noise in the signal. These experiments do not require the use of expensive optical components although access to the proper equipment would greatly facilitate the setup and alignment of the interferometer. The technique allows immediate return of the data and excellent measurement accuracy.

With electromagnetic gun developers requiring much stiffer railgun barrels this technique should provide a valuable tool for structural diagnostics and verification of finite element analysis. The measured deflections are not an indication of material strain or a prediction of material failure; however, the deflections obtained under the pulse loading can be used directly in designing obturators or contact compliance surfaces for solid armatures.

Acknowledgement

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