Railgun
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ABSTRACT
A railgun using electromagnetic propulsion was developed to launch hypervelocity projectiles. A 240 kJ, low inductance capacitor bank operating at 5 kV powered the railgun. Launchers and projectiles were designed and developed for this purpose. The currents producing the launch forces are of the order of hundreds of kA. Even very low impedances for the current through the railgun circuit are substantial sources of energy losses. A simulation code was developed to optimise the performance of the railgun. Control and instrumentation facilities were set up along with a computer-based data acquisition system for measurement and analysis. The capacity to launch projectiles of 3-3.5 g weight to a velocity of more than 2.00 km/s was demonstrated.

NOMENCLATURE

- \( A(t) \) projectile acceleration at time \( t \)
- \( E_{arc}(t) \) energy dissipated in plasma arc at time \( t \)
- \( E_i(t) \) energy of launcher at time \( t \)
- \( E_{proj}(t) \) kinetic energy of projectile at time \( t \)
- \( E_{total} \) total energy delivered by the power source
- \( F(t) \) force at time \( t \)
- \( I(t) \) current through the launcher at time \( t \)
- \( L \) inductance per unit length of the launcher
- \( L_{eff}(t) \) launcher efficiency at time \( t \)
- \( m \) mass of the projectile
- \( P(t) \) plasma pressure at time \( t \)
- \( P_{L_{eff}}(t) \) power source to launcher efficiency at time \( t \)
- \( S(t) \) displacement of the projectile at time \( t \)
- \( S_{eff}(t) \) total railgun system efficiency at time \( t \)
- \( v(t) \) velocity of the projectile at time \( t \)
- \( V_{br}(t) \) voltage at the breech end of the railgun at time \( t \)
- \( V_{elm}(t) \) velocity at the muzzle end of the railgun at time \( t \)
- \( V_{mv}(t) \) voltage at the muzzle end of the railgun at time \( t \)

1. INTRODUCTION
A facility was developed to launch hypervelocity projectiles using electromagnetic energy. The projectiles were launched using a railgun. The railgun consists of two parallel rails and a conducting metallic foil placed behind the insulating projectile. When a high current flows through the rails, the foil explodes and forms a plasma armature. The force acting on the armature is given by

\[ F(t) = 0.50 \times L \times I(t)^2 \]

The railgun currents are in the region of hundreds of kA. This Lorentz force accelerates the projectile. The railgun set-up is shown in Fig. 1.

2. POWER SUPPLY
An electromagnetic propulsion system requires a storage device with an energy density comparable to that of chemical explosives. The most expensive and technologically difficult part of the system is the high-energy electric source. The power sources considered for electromagnetic propulsion are well researched.
2.1 Capacitor Bank and Charging Unit

The capacitor bank was used as a power source owing to its availability and lower cost, despite its lower energy density. A low-inductance, 240 kJ capacitor bank was set up to provide the basic power to the railgun. A high-voltage charging unit was used to charge the capacitor bank.

2.2 High Current Switches

The capacitor energy is switched into the railgun by high-power ignitrons. When the peak current is reached, additional high-power ignitrons are used to crowbar the capacitors out of the circuit to obtain a dc pulse. This minimizes the stress on the capacitors, the launcher and the projectile. A schematic diagram of the railgun powered by the capacitor bank is shown in Fig. 2.

2.3 Transmission Lines

Low-inductance transmission lines were made using sandwiched conducting plates to maximize the energy transfer to the load. The transmission lines are subjected to repulsive forces owing to the passage of current through them. These forces were estimated to provide proper bolting and bracing to avoid deformation of the transmission lines.

3. LAUNCHER AND PROJECTILE

Launchers and projectiles are subjected to high plasma pressures, high magnetic fields and high temperatures. In the present railgun set-up, the plasma pressures generated varied between 100 and 150 MPa.

Launcher: A simple, single pulse driven railgun launcher was developed with a minimum of metal components in proximity to the bore to maximize the inductance of the launcher and to improve the launch efficiency. The launcher has a 12 mm square bore cross-section. The launcher was fabricated with lengths ranging from 1 to 2 m. The following launcher designs were used for the firings:

(a) The copper rails and the insulator were rigidly contained within Perspex side plates and bolted. These launchers were found to be weak, getting damaged and cracking at higher plasma pressures.

(b) The copper rails and the insulator were rigidly contained using fiberglass side plates and potted in an epoxy resin. The assembly was housed in a cylindrical mild steel jacket.

(c) The copper rails and the insulator were rigidly contained using fiberglass side plates and wound with a fiberglass material. They were potted in an epoxy resin and the assembly was housed in a cylindrical nonmetallic jacket.
4. DATA ACQUISITION AND SIMULATION

4.1 Data Acquisition

A computer-based data acquisition system was set up to monitor important parameters that affect the performance of the railgun. Current transformers and Rogowski coils were used to measure the rail currents in the range of 100 to 500 kA. Magnetic probes were used to get the position–time profile of the projectile inside the bore of the gun and railgun current distribution. These probes help detect plasma leakage and formation of secondary arc. The velocity outside the bore of the gun was measured using shorting screens. A high-speed camera was set up to measure the velocity of the projectile and establish the integrity of the projectile at the muzzle end. This is a non-contact method and is free from electromagnetic pickups.

4.2 Simulation

A simulation code was developed to predict the performance of the railgun. The performance of the model was evaluated by monitoring different parameters. Table 1 gives the equation used in the simulation and analysis. The current measured is used to derive other significant parameters like the displacement, velocity and acceleration of the projectile calculated from Eqns (1) – (3).

![Figure 3. Construction details of the railgun.](image)

**Table 1. Equations used for the analysis of the railgun system**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S(t)$</td>
<td>$\frac{[L/(2m)]}{2} \int f I(t)^2 , dt$</td>
</tr>
<tr>
<td>$V(t)$</td>
<td>$\frac{[L/(2m)]}{2} \int f I(t)^2 , dt$</td>
</tr>
<tr>
<td>$A(t)$</td>
<td>$\frac{[L/(2m)]}{2} \int f I(t)^2 , dt$</td>
</tr>
<tr>
<td>$P(t)$</td>
<td>$\frac{[L/2]}{2} \int f I(t)^2 , dt$</td>
</tr>
<tr>
<td>$F(t)$</td>
<td>$\frac{[L/2]}{2} \int f I(t)^2 , dt$</td>
</tr>
<tr>
<td>$E_r(t)$</td>
<td>$V_m(t) \int f I(t)^2 , dt$</td>
</tr>
<tr>
<td>$P_{\text{eff}}(t)$</td>
<td>$E_r(t)/E_{\text{eff}}$</td>
</tr>
<tr>
<td>$L_{\text{cor}}(t)$</td>
<td>$E_{\text{proj}}(t)/E_{\text{cor}}(t)$</td>
</tr>
<tr>
<td>$E_{\text{Kin}}(t)$</td>
<td>$V_m(t) \int f I(t)^2 , dt$</td>
</tr>
<tr>
<td>$E_{\text{proj}}(t)$</td>
<td>$(1/2) \int m \int f V(t)^2$</td>
</tr>
<tr>
<td>$S_{\text{eff}}(t)$</td>
<td>$E_{\text{proj}}(t)/E_{\text{eff}}$</td>
</tr>
</tbody>
</table>

5. ANALYSIS

All measurements were supported by appropriate software developed to analyse the entire performance
6. RESULTS

Some typical railgun trial results are given in Table 2. Projectile velocities greater than 2000 m/s were obtained for trial nos 1 to 3. The efficiency varied between 4 to 5 per cent with railgun current in excess of 260 kA.

Plasma leakage and formation of secondary arcs were responsible for the lower projectile velocities than expected from the computer model for trial nos 5 to 7. Trial no. 7 was done using a solid conducting projectile made of aluminium. An armature was kept behind the projectile with no ablator. The armature vaporised and the plasma escaped ahead of the projectile. This led to a lower system efficiency and projectile velocity.

A solid projectile made of Perspex and armature made of several copper foils were used in trial no. 4. The mass of each foil was kept around 100 mg to avoid the melting of the armature owing to the high railgun current.

7. CONCLUSION

Our study has shown that projectiles attain hypervelocities by using a single small square bore railgun. In the existing railgun facility the efficiency varied between 4 to 5 per cent. Significant improvement in the efficiency of the railgun set-up is one of the key issues that will determine the use of railguns for various weapon applications. Hence we carried out detailed modelling and simulation of the entire railgun system. The results from the simulation were validated with the measurements. Measurements made at high common mode voltages of around 1000s of volts and high electromagnetic noise were exceptionally good, providing reliable and repeatable records. Intact projectile launch and 2-3 m of free flight projectile were studied using high-speed photography when punctures in the shorting screens were observed. Using a high-speed camera the integrity of the projectile was established beyond doubt (Fig. 5). A 12 mm cubical polycarbonate projectile weighing about 3 g could defeat a 6 mm aluminium sheet at 2 m from the muzzle end of the gun (Fig. 6). The complete railgun system was also placed in a 5 m long vacuum chamber to study the railgun performance. Our studies are as yet inconclusive. Owing to the failure of some odd capacitors in the capacitor bank, repetitive trials could not be carried using the full energy of the bank. The energy extracted from the
Table 2. Some typical railgun results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of projectile, g</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.7</td>
<td>3.0</td>
<td>7.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Type of armature</td>
<td>Plasma</td>
<td>Plasma</td>
<td>Plasma</td>
<td>Solid</td>
<td>Plasma</td>
<td>Solid</td>
<td>Plasma</td>
</tr>
<tr>
<td>Peak, kA</td>
<td>298.0</td>
<td>296.0</td>
<td>290.0</td>
<td>267.0</td>
<td>271.0</td>
<td>287.0</td>
<td>234.0</td>
</tr>
<tr>
<td>Peak force on the projectile, kN</td>
<td>22</td>
<td>21</td>
<td>21</td>
<td>18</td>
<td>18</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Peak acceleration on the projectile, k'g'</td>
<td>740</td>
<td>730</td>
<td>700</td>
<td>491</td>
<td>624</td>
<td>300</td>
<td>466</td>
</tr>
<tr>
<td>Peak pressure, MPa</td>
<td>154</td>
<td>152</td>
<td>146</td>
<td>123</td>
<td>128</td>
<td>143</td>
<td>95</td>
</tr>
<tr>
<td>Theoretical projectile velocity, m/s</td>
<td>2250</td>
<td>2250</td>
<td>2250</td>
<td>1730</td>
<td>2150</td>
<td>1250</td>
<td>2200</td>
</tr>
<tr>
<td>Measured projectile velocity, m/s</td>
<td>2080</td>
<td>2050</td>
<td>2000</td>
<td>1550</td>
<td>1700</td>
<td>588</td>
<td>1300</td>
</tr>
<tr>
<td>Kinetic energy of the projectile, kJ</td>
<td>6.49</td>
<td>6.30</td>
<td>6.00</td>
<td>4.44</td>
<td>4.35</td>
<td>1.20</td>
<td>2.56</td>
</tr>
<tr>
<td>System efficiency, %</td>
<td>4.69</td>
<td>4.56</td>
<td>4.34</td>
<td>2.58</td>
<td>3.13</td>
<td>0.87</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Figure 5. A polycarbonate projectile photographed through an Imacon high speed camera (framing speed: 500,000 frames/s; exposure time: 400 ns; flash duration: 500 μs; and aperture: 4).
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REFERENCES


