The Structural Response of a Rail Accelerator

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Abstract

The transient response of a 0.4 by 0.6 cm rectangular bore rail accelerator was analyzed using a three-dimensional finite-element code. Results are presented for the case of a 210-kA current input and 5-cm arc length. Typically, the copper rail deflected to a peak value of 0.03 mm in compression and then oscillated at an amplitude of 0.02 mm. Simultaneously the insulating side wall of glass fabric base, epoxy resin laminate (G-10) was compressed to a peak value of 0.13 mm and rebounded to a steady state in extension. Projectile pinch or blow-by due to the rail (or side-wall) extension or compression, respectively, can be identified by examining the time history of the rail (or side-wall) displacement. For the case presented, the effect of blow-by was most significant at the side wall characterized by mm-size displacement in compression.

Dynamic stress calculations indicate that the G-10 supporting material behind the rail is subjected to over 21 MPa— at which the G-10 could fail if the laminate was not carefully oriented. Results for a polycarbonate resin (Lexan) side wall show much larger displacements and stresses than for G-10. Therefore the tradeoff between the transparency of Lexan and the mechanical strength of G-10 for side-wall material is obvious.

Displacement calculations from the modal method are smaller than the results from the direct integration method by almost an order of magnitude, because the high-frequency effect is neglected. However, this effect is significant and dominating for a highly-impulsive, wave-propagation problem such as the rail accelerator structure.

Introduction

A rail accelerator imparts high velocity to a projectile through the application of large impulsive forces of short duration. For the case of a plasma armature, the rail accelerator structure is dynamically stressed by the plasma pressure and magnetic forces immediately behind the projectile. The impulsive loading causes stress waves to propagate through the structure inducing responses in the materials at the wave speed. Displacements of the rails and insulating side walls ahead of the projectile may hinder the performance of the accelerator due to a combination of two effects: pinch and blow-by. The former occurs when the rails or side walls pinch into the projectile and frictional interaction intensifies; the latter occurs when the clearance between the projectile and the rails or side walls opens allowing the plasma to blow by the projectile. These effects can be detrimental if the design of the rail and supporting structures are insufficient to handle the intensive pulse loading of hundreds of megapascals.

Numerical analysis can be used to estimate the structural response of the rail accelerators. For some rail geometries, one or two-dimensional analyses have been applied to estimate the maximum rail deflections and the relative effects of different structural or material properties. However, it is desirable to use a three-dimensional transient program to model a rail accelerator structure to visualize the transient deflections of the rail in three dimensions as well as the propagation of the stress wave.

The primary purpose of this paper is to predict the transient rail and side-wall displacements of a 0.4 by 0.6 cm rectangular bore, one meter long rail accelerator using the three-dimensional finite-element code MARC on CRAY/IBM computers. Both rail and side wall deflections are estimated by applying a pulsed plasma loading on both the side wall and the rail and a magnetic loading on the rail behind the projectile.

A secondary purpose is to calculate the stress of the supporting materials, including a glass fabric base, epoxy resin laminate (G-10), a polycarbonate resin (Lexan), and a phenolic resin.

Results are presented using the Newmark direct integration method for a typical case of 210-kA current input, with a 5-cm plasma arc length at an instantaneous velocity of 2.5 km/s. A modal method using 10 modes is also used for comparison.

Analytical Procedures

When a material is subjected to a significant dynamic loading, disturbances are propagated through the body as stress waves. Deformations resulting from the impulsive loading will be highly localized within the region influenced by the stress wave, while the global structural effect is small. For this case wide-spectrum frequencies are excited; however, the high-frequency effect is significant and dominating for a highly-impulsive, wave-propagation problem such as the rail accelerator structure.

Finite-element Code

The three-dimensional finite-element code, MARC, is available in both modal and direct integrating method. The former allows a choice of 10 modes and is generally good for low-frequency structural dynamic problems. The latter is appropriate for high-loading, wave-propagation problems such as the rail accelerator. The direct Newmark integration method was selected for the analysis, and the 10-mode modal method was used for comparison purposes.

The finite element mesh plot was generated and shown in Fig. 1(a). Only a quadrant of the rail accelerator, of Figs. 1(b) and (c), is needed because of two planes of symmetry. The element used is an 8-node, isoparametric, three-dimensional hexahedron block. The mesh model consists of 300 elements and 544 nodes. A typical run on the CRAY-1S uses about 18 minutes (in CPU). All the outputs and post plots are then transferred to a front computer the IBM 3033.

For the cases studied, the materials used for the rail accelerator were held within the elastic limits. Any plastic distortion or non-linear effect is undesirable. Furthermore, the secondary effect of damping is not included in this report which represent the upper bound values of both displacement and stress.

Input Conditions

A rail accelerator one meter long with a bore of 0.4 by 0.6 cm was simulated. Rails are made of copper, and side-wall and supporting structures are made of G-10/Lexan and phenolic resin. Their properties are

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Input Conditions

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listed in Table I. A high current plasma armorature was produced to accelerate the projectile between the rails.

Referring to Fig. 1, the projectile is set to a starting position (reference nodal point 2) and is accelerated by the arc plasma covering bore walls of element numbers 1 and 2 through the muzzle end. The projectile, all the way through to the muzzle end (reference nodal point 21).

**Loading Conditions**

Loading inputs include both arc plasma pressure ($P_{ap}$) and rail magnetic pressure ($P_r$). $P_r$ is acting on the back of the projectile of an area ($A_r$) and is proportional to the Lorentz force ($F_p$). $F_p$ is obtained from the input current (I) and the inductance gradient ($L'$) of the rail:

$$ F_p = \frac{L'}{L_L} I^2 $$

where $h$ is the rail height, and $s$ is the distance between the rails. $P_r$ is equal to the magnetic force ($F_{pp}$) per unit rail area ($A_r$) and is acting on the rail only:

$$ P_r = \frac{L'}{L_L} I^2 . \frac{dL}{dS} $$

where $h$ is the arc plasma height, and $dL/dS$ is the inductance gradient calculated for this geometry. [7]

It is assumed that $P_{ap}$ is uniformly distributed behind the projectile within an arc length ($L_a$). The acting period of time ($at$) of $P_{ap}$ on a specific element wall is then $L_a/V_m$, where $V_m$ is the instantaneous speed of the projectile traveling through the bore, and $L_a$ can be estimated by combining available measured values [8,9] and the scaling laws. [10]

Typical values used for the calculations are listed in Table II.

For illustration, the transient pressure inputs are plotted in Fig. 2 for rail elements 1 through 4, and also for side-wall elements 241 through 244. Where a flat-topped pulse of 20 usec is assumed for $P_{ap}$ of 450 MPa and a constant $P_r$ is 240 MPa. With known arc length and speed, only the arc shape is assumed for the transient loading input.

Different pulse shapes of inertia loading and responses have been well investigated. [11] The square wave renders the maximum response, by an amplification factor of two, as compared to other shapes: sinusoidal, triangular, sudden-rise, or sudden-fall. The flat-topped shape pulse assumed in the paper should give more conservative values of displacement, although the actual shape of loading may be quite complicated.

**Results and Discussions**

The primary case (P41) is calculated using G-10 as the side-wall insulator and applying the direct integration method. Two secondary cases are included for the comparison of using transparent Lexan as the side-wall material (Case Q41) and for applying the modal method with ten modes (Case Q41).

The Primary Case (P41)

Time history results are presented for both rail and side-wall displacements, the element stress of G-10 backing material behind the rail, and the sectional stress contours of case P41.

Figure 3 shows the rail displacements at the breech end (nodes 1 and 2) and the muzzle end (nodes 20 and 21). Each nodal point has a similar response characterized by a pulse due to the impulsive loading and then approaching a quasi-steady value. Figure 4 shows that the transient response of a single node 3, G-10 case shown in Fig. 6, and the effect of applying the modal method with ten modes (Case Q41).
displacements are much smaller. On the other hand, periods are larger when compared with Fig. 4. The reason for these differences is the modal method does not include enough modes so that the dominating effects of high frequencies of the wave are neglected. On the other hand, the direct integration method is appropriate for the highly impulsive, wave-propagation problem such as the rail accelerator.

Concluding Remarks

The response of a rail accelerator structure to an impulsive loading can be predicted by a three-dimensional, finite-element code - MARC using the direct integration method. The effects of blow-by or pinch are shown by rail or side-wall displacements. Mechanical limits are also discussed to the first order by calculating the dynamic stress values. Relative merits of different materials or geometry can readily be assessed.

References

### TABLE I. - PROPERTIES OF RAIL ACCELERATOR MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's Modulus, GPa</th>
<th>Poisson Ratio</th>
<th>Density, gm/cm³</th>
<th>Yield Point, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>117</td>
<td>0.37</td>
<td>8.4</td>
<td>400</td>
</tr>
<tr>
<td>G-10 Laminate</td>
<td>17.2</td>
<td>0.33</td>
<td>1.75</td>
<td>7-350*</td>
</tr>
<tr>
<td>Lexan</td>
<td>2.3</td>
<td>0.33</td>
<td>1.2</td>
<td>63</td>
</tr>
<tr>
<td>Phenolic Resin</td>
<td>8.3</td>
<td>0.33</td>
<td>1.4</td>
<td>45</td>
</tr>
</tbody>
</table>

*Depends on orientation of the laminates.

### TABLE II. - VALUES USED FOR CALCULATIONS

<table>
<thead>
<tr>
<th>Current I, KA</th>
<th>Arc length, Lₐ, cm</th>
<th>Velocity Vₐ, km/s</th>
<th>Inductance gradient L', µh/m</th>
<th>Inductance gradient dL'/d(S/h), µh/m</th>
<th>Rail height h, cm</th>
<th>Arc height h_p, cm</th>
<th>Rail width s, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>5</td>
<td>2.5</td>
<td>0.48</td>
<td>0.245</td>
<td>0.63</td>
<td>0.38</td>
<td>0.63</td>
</tr>
</tbody>
</table>
Figure 1.

(a) Mesh plot of the 0.4x0.6 cm rail accelerator.
A quadrant between two symmetric planes is used for modeling.

(b) Rail accelerator cross section.

Figure 1. - Continued.
(c) Rail accelerator (gun).

Figure 1. - Concluded.
Figure 2. - Transient profiles of pressure loading for the first four elements of both the rail (1-4) and side wall (241-244).
Figure 3. - Rail displacements at breech and muzzle ends.
A COMPRESSION OF 0.03 mm INDICATES POSSIBLE BLOW-BY: THE PLASMA LEAKS TO THE FRONT OF THE PROJECTILE.

Figure 4. - Rail displacement 5-cm downstream.

Figure 5. - Side-wall displacements at breech/muzzle ends.
Figure 6. - Side-wall G-10 displacement 5-cm downstream.

Figure 7. - Stress in G-10 backing material 5-cm downstream.
Figure 8. - Transient stress contours for copper rail (elements 61-80), G-10 backing (elements 81-100), and G-10 siding (elements 241-260).
Figure 9. - Displacements 5-cm downstream using lexan.

Figure 10. - Displacements 5-cm downstream modal method.
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17. Key Words (Suggested by Author(s))

Propulsion
Rail gun
Structure dynamics