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Abstract—This publication describes electromagnetic and structural analyses of electric gun and integrated launch packages. Models presented were developed for the Sabot Launched Electric Gun Kinetic Energy projectile (SLEKE) program and the Cannon Caliber Electromagnetic Launcher (CCEML) program. Analyses were three-dimensional, transient and coupled with thermal calculations including dynamic material properties. In the SLEKE analysis section we focus on electromagnetic and structural performance of integrated launch packages. SLEKE analyses have been validated by successful launch of test articles at maximum design levels. CCEML launch package and barrel performance has been studied in detail which benefits from experience gained in the SLEKE program. CCEML analyses presented focus on augmented launcher performance.

INTRODUCTION

Three-dimensional (3-D) modeling is critical for electromagnetic (EM) and structural analyses of viable EM gun launch packages and barrels. Two-dimensional (2-D) armature/rail models are limited to uni-directional (perpendicular to the plane of the problem) magnetic field vectors and planar (in the plane of the problem) current and force vectors. In reality these vectors are three-dimensional although 2-D models have been used for qualitative studies of complex EM gun problems such as armature velocity skin effect [1]. We present two examples of 3-D analyses: SLEKE integrated launch package and CCEML barrel.

We will discuss common aspects of our analysis models in the first section. Next, the SLEKE section will give detailed results on EM and structural models for the launch package currently being tested under that program. CCEML models are presented to provide insight as to the EM performance of a medium-caliber augmented launcher and shows that current diffusion dramatically effects the launcher EM performance; augmented launchers must be modeled in 3-D to insure accurate prediction of gun performance.

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GENERAL ANALYSIS MODEL

EM models consist of rail, solid armature/sabot, subprojectile and air. For a given total gun current waveform, the 3-D finite element model calculates transient current density, magnetic field, EM force and temperature distributions in all conductor regions [2,3]. EM and thermal calculations are coupled and material properties are temperature dependent. Rail/armature electrical contact has been modeled as galvanic. Effects of armature motion have been neglected.

Total gun current (I) is input through electric potential (V) at the breech end of the rails. In the transient case,

$$V = RI + \frac{d(LI)}{dt} \quad (1)$$

in which rail resistance (R) and rail inductance (L) are unknown until the problem is fully solved. In order to obtain a direct relationship between V and I , models are slightly modified by adding a short rail section at the breech end (temperature independent, pseudo-resistance, R_p). As the added section is very short, its presence does not disturb the rail inductance.

$$V = RI + \frac{d(LI)}{dt} + R_p I \quad (2)$$

If we choose the value of R_p such that $R_p \gg R$, then

$$I \cong \frac{1}{R_p} V \quad (3)$$

which lets us input I by prescribing V at the breech end.

Armature material resistivity and specific action data used are listed in table 1. To obtain accurate armature material data, we performed armature material specific action tests where lead-acid batteries supplied 2 to 3 kA of current through a test specimen (0.125 in. diameter) until melting of the specimen naturally opens the circuit within 0.5 to 1 s. Resistivity, specific action and temperature values were mea-

sured up to and slightly above the material melting temperature. Specific action measured was $19,800 \text{ A}^2\text{s/mm}^4$ at the beginning of melt. Data of pure aluminum, tested by Tucker and Toth [4] were used after offsetting values by the difference at melting for the temperature range above melting.

Table 1. Solid armature electrical resistivity input data for EM analysis, armature material is aluminum 7075 T651

	Aluminum 7075 T651 (EM Analysis input)				Pure Aluminum (Tucker and Toth)	
	Resistivity ($\mu\Omega\text{-cm}$)		Specific Action ($\text{A}^2\text{s/mm}^4$)		Resistivity ($\mu\Omega\text{-cm}$)	Specific Action ($\text{A}^2\text{s/mm}^4$)
Room Temperature	5.5	CEM	0		2.8	0
Melting Begins	12.0	CEM	19800	CEM	11.2	25238
Melting Ends	23.1	Tucker	26597	Offset	23.1	32035
Vapor Begins	41.5	Tucker	43123	Offset	41.5	48561
Burst	393.0	Tucker	60338	Offset	393.0	65776

CEM = CEM-UT material test results
Tucker = Tucker and Toth test results [4]
Offset = Offset from Tucker and Toth data by $5438 \text{ A}^2\text{s/mm}^4 (= 25238 - 19800)$

Structural analysis models include interface elements at rail/armature contact in addition to elements used for conductors within the EM model. The structural analysis routine ABAQUSTM was used in each case. EM and structural analysis meshes were identical, so EM force data at Gauss points and nodal temperature data could be passed to the structural model without interpolation. Friction at the rail/armature contact was neglected. All loads were treated as quasi-static; dynamic effect of EM load was neglected. Initial interference calculation is done first to determine the initial stress state in the armature. Interference profiles have been calculated and used in tests of actual designs. Following simulation of armature insertion conditions, EM forces and temperatures tracing the EM analysis steps were applied. Inertial load (material density times total EM drive force divided by package mass) is then applied to the package.

Armature material strength was modeled as temperature dependent and increases with increasing heating and strain rates relative to long time at temperature properties. Although the present application loading rate is on the order of a few milliseconds to melting and/or fracturing, tensile strength data for heating and fracturing for 0.5 s heating rates were used [5] (only available data found in literature). Yield stress to tensile strength ratio was assumed to be a constant and provided reduced yield stress and elongation estimates based on the 0.5 s data. The material model used in our analysis (bilinear elastic-plastic) is listed in figure 1. Data for 30 minute test duration are also shown for comparison purposes [6].

Figure 1. Tensile strength, yield strength and elongation input data of aluminum 7075 T651 as functions of temperature; based on test data by Griffis [5] (0.5 s data) and Van Horn [6] (0.5 hour data)

SLEKE ANALYSIS RESULTS

A quarter symmetry model of 90 mm round bore rail and a SLEKE package (single armature, mid-drive, SAMD 5.1 (fig. 2) with full length tungsten projectile was analyzed. Gun current waveform for 6 MJ muzzle kinetic energy with two power supply current staging events (fig. 3) were input. The first current peak (step 2) represents the highest mechanical and lowest thermal loads in the package. Current density vectors at the first current peak are shown in figure 4. Most transport current and drive force appear at the rear and side faces of the armature and diffuse into the bulk with time. Structural analysis predicts high stress and strain values at the rear root region of the armature. Local yielding occurs but is not severe enough to cause material failure for this case.

Figure 2. SLEKE mid-drive, integrated launch package (SAMD5.1)

Figure 3. Gun current input data for 6 MJ EM analysis

Figure 4. Current density results vector plot (A/mm^2) at step 2: first current peak, time = 1.0 ms, gun current = 3.0 MA

Total package force components at each of the time steps are listed in table 2. Magnitudes of F_x (magnetic contact force) and F_y (attractive force between the two armature halves) components are over half the total magnitude of the drive force, F_z . This suggests that even a small amount of asymmetric transverse force (or asymmetric transport current distribution) can lead to severe and potentially unstable lateral loads on the package.

Figure 5 shows armature temperatures at the second current peak (step 5). The second current peak represents the highest combined mechanical and thermal loads in the package. Highest risk of package failure is typically encountered at the last current peak. As shown in figure 5, some melting

is predicted at the rear root region of the armature (material data was input such that melting begins at $T = 600^\circ\text{C}$). Figure 6 shows Mises stress distribution at the second current peak. It shows stress redistribution to nearby cooler areas as the rear root region of the armature is heated. Plastic strain values (fig. 7) are low everywhere except for the rear root region, where strain values are high and unstable.

Table 2. EM force results

SAMD5 Armature
6 MJ, 2 Peak Gun Current
Cross Section Area of Contact = 3.05 in.²
Bore Diameter = 3.626 in.

Step	Time [ms]	Current [MA]	Action [1 eq A ² s]	Specific Action [A ² s / mm ⁴]	Fx: Rail-Rail Dir. [k lb]	Fy: Ins.-Ins. Dir. [k lb]	Fz: Drive [k lb]
0	.0	.000	.0	0	.0	.0	.0
1	.5	1.098	.2	52	30.7	-21.7	50.2
2	1.0	3.006	2.5	639	247	-168.7	385.2
3	2.0	2.764	10.8	2,804	249.7	-168.3	346.7
4	3.5	2.248	20.2	5,262	167.2	-130.8	241.6
5	3.6	2.895	20.9	5,434	233.6	-186.7	369.2
6	5.0	2.132	29.8	7,751	144.7	-127.4	224.2
7	7.0	1.339	35.9	9,345	53.4	-59	96.6
8	8.5	.966	38.0	9,867	24.8	-32.9	53.6

Figure 5. Temperature rise results contour plot ($^\circ\text{C}$) at step 5: second current peak, time = 3.6 ms, gun current = 2.9 MA, electric action = $20.9 \times 10^9 \text{ A}^2\text{-s}$

Muzzle exit (step 8) represents the most severe thermal but lowest mechanical loads in the package. The size of the melted region is slightly larger than that corresponding to the second peak, but stress values are low due to low magnetic loads.

Combined EM and structural analysis results were used as a guide to assess launch package design viability at 6 MJ launch energy. Model prediction that the package would survive launch was validated by successful firing of test articles at maximum design levels of 3.1 MA peak current and 6.6 MJ muzzle kinetic energy [7].

Figure 6. Mises stress results contour plot (ksi) at step 5: second current peak, time = 3.6 ms, gun current = 2.9 MA

Figure 7. Plastic strain results contour plot (%) at step 5: second current peak, time = 3.6 ms, gun current = 2.9 MA

CCEML LAUNCHER INDUCTANCE GRADIENT MODELING

Accurate determination of the launcher driving inductance gradient (L') and time dependent inductance is critical for proper sizing of armature mass and specification of launcher terminal characteristics parameters which are a prerequisite for optimization of the pulsed power supply used to drive the gun [8]. Two analytical methods (2-D and 3-D) were used to predict these launcher parameters in CCEML.

A 2-D high frequency algorithm [9] calculates launcher L' based on inductive energy considerations. By assuming high frequency conditions, all currents reside in the conductor surface and transient current diffusion into the conductors is

neglected. 3-D EM models include field/current diffusion effects and calculate launcher driving L' from the total driving force components in the launch package. Launcher magnetic energy L' (same approach as high frequency analysis except that current diffusion effects are included) is calculated from magnetic field values on 2-D slices of the 3-D model at some distance behind (L'_{eff}) and forward (L'_{aug}) of the armature (to eliminate 3-D geometry effects in the vicinity of the armature).

In EM guns utilizing only two rails, the two methods provide essentially identical (at early times in the launch event modeled) and conservative driving L' values which may be used in the launcher design process. However, in the case of augmented launchers, the high frequency method has proved to overestimate driving L' and to underestimate magnetic energy L' compared to demonstrated values. This is due to diffusion of the magnetic field of the augmenting turns into the main rails and results in a lower effective driving L' . 3-D analyses predict a lower driving L' and higher energy L' than that predicted with the high frequency method. The effective driving L' of 3-D models has been found to be typically 10 to 15% lower than that predicted with the high frequency method, while the magnetic energy L' of 3-D models is up to 25% higher.

A critical aspect of these analyses is the dependence of the power supply design on driving L' and magnetic energy L' values. In terms of electrical impedance, the power supply must be designed to drive the inductances of magnetic energy L'_{eff} and L'_{aug} obtained with the 3-D analyses models although only the $J \times B$ driving L' is useful in accelerating the launch package. More importantly, the augmenting turn inductance (L'_{aug}) is a strong driver of power supply machine mass; as L'_{aug} increases, so does machine mass. For these reasons, a primary focus of launcher design in the CCEML program has been to insure accurate prediction of driving and magnetic energy L' values and rail resistive losses so that the power supply size and mass may be appropriately determined [8,10].

Based on the results of EM analysis iterations, the launcher configuration with augmenting turns located directly behind the main rails and a 85 g, tandem contact armature was selected [8,10]. A sinusoidal current waveform with a peak of 780 kA and duration of 2 ms was modeled in a sequence of six time steps. Figure 8 shows main rail, armature, flat-jack and augmenting turn relative temperature rise at muzzle exit. Table 3 gives final optimized performance parameters and lists launcher driving and magnetic energy L' values, rail repulsion loads, armature driving force, and rail resistive energy losses. Average L' values were used in determining power supply design requirements. Time-dependent main rail and augmenting turn effective resistance is calculated by dividing resistive energy per unit length by the total action. Effects of current diffusion into the rails is evident by observing that rail resistance values decrease with time. An energy balance for launcher performance is also provided in table 3.

Table 3. CCEML launcher performance parameters

Step	Time [s]	Inductance Gradient Parameters				Rail Force		Aug. Turn Force		Arm. Force
		L' drive (JxB) [H/m]	L' tot (Mag. Energy) [H/m]	L' aug (Mag. Energy) [H/m]	L'eff =L' tot - L' aug (Mag. Energy) [H/m]	Fx (total) [klb/in]	Fy (symmet.) [klb/in]	Fx (Total) [klb/in]	Fy (symmet.) [klb/in]	Fz (total) [klb]
1	0.00047	1.11E-06	1.79E-06	5.85E-07	1.20E-06	15.2	-8.3	-1.1	-2.6	35
2	0.00076	1.12E-06	1.87E-06	6.40E-07	1.23E-06	29.7	-16	-2.3	-5.6	68
3	0.001	1.12E-06	1.95E-06	6.92E-07	1.26E-06	33.5	-17.9	-2.9	-6.7	75.9
4	0.00124	1.11E-06	2.03E-06	7.39E-07	1.29E-06	30.6	-16.1	-3.1	-6.6	68.3
5	0.00153	1.10E-06	2.21E-06	8.58E-07	1.36E-06	16.6	-8.7	-2.2	-4.1	35.8
6	0.002	N/A	N/A	N/A	N/A	0.3	-1.1	-0.2	-0.2	0.2
Average		1.11E-06	1.97E-06	7.03E-07	1.27E-06					

Step	Time [s]	Action [A ² s]	Launcher Resistive Energies				Launcher Resistance		
			Erail [J]	Eaug [J]	Total [J]	Erail [J/m]	Eaug [J/m]	R' rail (total) [Ω/m]	R' aug (total) [Ω/m]
1	0.00047	4.39E+07	7,537	7,620	15,156	11,640	4,119	2.65E-04	9.39E-05
2	0.00076	1.61E+08	19,691	21,046	40,737	30,411	11,376	1.89E-04	7.07E-05
3	0.001	2.98E+08	31,754	35,992	67,746	49,041	19,455	1.64E-04	6.52E-05
4	0.00124	4.37E+08	41,939	50,442	92,381	64,770	27,266	1.48E-04	6.24E-05
5	0.00153	5.56E+08	49,406	62,959	112,365	76,303	34,032	1.37E-04	6.12E-05
6	0.002	6.02E+08	56,604	72,611	129,214	87,419	39,249	1.45E-04	6.52E-05

Energy Balance							Launch Package Parameters			
Package KE [J]	Rail Resistive Energy [J]	Aug. Turn Resistive Energy [J]	Armature Resistive Energy [J]	Armature Arc Energy [J]	Total Breach Energy [J]	Breach Efficiency [%]	Launcher Active Length [m]	Launch Package Mass [kg]	Launch Velocity [m/s]	Launch Kinetic Energy [J]
316,581	56,604	72,611	13,500	71,500	530,796	59.64	1.85	0.185	1,850	316,581

CONCLUSIONS

SLEKE Launch Package

(1) Combined EM and structural analysis results presented were used as a guide to assess launch package design viability at 6 MJ launch energy. Model prediction that the package would survive launch was validated by successful firing of test articles at maximum design levels [7].

(2) Armature resistivity and specific action data and temperature dependent armature material strength data were obtained and used in the analyses presented. The material data are currently being tested against sub-scale EM launch test results [7].

(3) Ablation of contact surface material due to arcing in the sliding interface can cause excessive contact bending stress. The issue of contact ablation must be addressed in future designs to insure successful launch at higher energy.

(4) Effects of armature motion on the rail/armature sliding interface condition must also be modeled in 3-D to fully treat this dynamic process.

Figure 8. CCEML launcher and armature relative temperature at muzzle exit (°C)

CCEML Barrel and Launch Package

(1) 3-D EM models provide accurate launcher driving L' and magnetic energy L' values for both simple and augmented rail configurations, while 2-D high frequency models provide accurate L' only for simple rail configurations.

(2) 3-D EM model results were used for final launcher performance evaluations in CCEML. Calculated performance parameters include launcher driving and magnetic energy L' values, main and augmenting rail forces, launcher resistive energy and resistance values, launcher energy balance calculations, all of which are essential for characterization of pulsed power supply demand.

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