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Numerical simulation of interior ballistic process of railgun based on the multi-field coupled model

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Abstract

Railgun launcher design relies on appropriate models. A multi-field coupled model of railgun launcher was presented in this paper. The 3D transient multi-field was composed of electromagnetic field, thermal field and structural field. The magnetic diffusion equations were solved by a finite-element boundary-element coupling method. The thermal diffusion equations and structural equations were solved by a finite element method. A coupled calculation was achieved by the transfer data from the electromagnetic field to the thermal and structural fields. Some characteristics of railgun shot, such as velocity skin effect, melt-wave erosion and magnetic sawing, which are generated under the condition of large-current and high-speed sliding electrical contact, were demonstrated by numerical simulation.

Keywords: Railgun; Electromagnetic field; Thermal field; Structural field; Finite element; Numerical simulation

1. Introduction

The application of electromagnetic force in defense technology is receiving more and more attention [1]. Research on the interior ballistics of railgun requires the detailed analysis of launch components, such as armature and rail, which exhibit the coupled electromagnetic, thermal and structural behaviors. The accurate numerical simulation and modeling of electromagnetic process are crucial to treat the multi-field coupled problem. But some features of a railgun launcher make it difficult to model: the railgun launcher is inherently three-dimensional, and the high-speed sliding electric contact between rail and armature is involved during a railgun shot. Some computer programs, such as EMAP3D [2], MEGA [3] and HERB [4], were developed to simulate the electromagnetic diffusion process under the condition of high-speed sliding electric contact. Recently, an electromagnetism module was added to the LS-DYNA dynamics analysis software [5] for the coupled mechanical/thermal/electromagnetic simulations.

Besides the electromagnetic field analysis, the thermal and structural aspects are becoming even more important at the weapon level currents conducted in rails and armature. Many potentially interesting features, such as structural deformation and armature melting, can be obtained more easily from numerical simulation than from experiment.

The models, algorithms and results of the multi-field analyses for railgun were presented in the paper. The electromagnetic and thermal equations were solved by an in-house program code. The simulated results of electromagnetic field were transferred as forcing functions to the structural module of LS-DYNA, and the structural dynamic responses of a railgun were obtained.

2. Theoretical model and numerical method

2.1. Basic assumptions

The load transfer methods were used to couple the electromagnetic, thermal and structural fields. The results of electromagnetic analysis were transferred to the thermal and structural analyses. In order to facilitate the multi-field computation, the following assumptions were made: (a) only metallic components, such as armature and rail, were considered in a model; (b) the nonlinear properties of materials were ignored; (c) the contact surface between armature and rail was smooth; (d) one-way coupling was used, and the calculation of the electromagnetic field provided ohmic heating power loads for thermal conduction and Lorentz force loads for structural field.

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2.2. Magnetic diffusion equations

The electromagnetic field was modeled by magnetic diffusion equations in the Lagrange coordinate system. Using the magnetic vector potential $\vec{A}$ and electric scalar potential ϕ as unknown quantities, a set of magnetic diffusion equations, which can be deduced from quasi-static Maxwell's equations, is expressed as

$$\begin{cases} \nabla\times\frac{1}{\mu}\nabla\times\vec{A}=\sigma\left(-\frac{\mathrm{D}\vec{A}}{Dt}-\nabla\phi\right) \\ \nabla\cdot\left[\sigma\left(-\frac{\mathrm{D}\vec{A}}{\mathrm{D}t}-\nabla\phi\right)\right]=0 \end{cases} \tag{1}$$

where μ is the permeability of conductors and σ is the electrical conductivity. For non-conductive regions, the Laplace equation can be deduced form Eq. (1) due to negligible electrical conductivity.

A hybrid finite element and boundary element coupling algorithm was used in the calculation of the magnetic diffusion equations [6]. The finite-element formulation based on the Galerkin form of weighted residuals method was used for the magnetic diffusion equations for the conductive region including rail and armature. The discretized magnetic equations are approximated by the following matrix form as

$$\left(\mathbf{K}+\frac{\mathbf{M}}{\Delta t}\right)\cdot[\mathbf{A}]^{n+1}=\frac{\mathbf{M}}{\Delta t}\cdot[\mathbf{A}]^{n}-\mathbf{P}\cdot[\varphi]^{n+1}+\mathbf{S}\cdot\left[\frac{\partial\mathbf{A}}{\partial n}\right]^{n+1} \tag{2}$$

where **K**, **M**, **P** and **S** are the coordinate matrices. For the non-conductive region, the boundary element formulation was used for Laplace's equation. The boundary integral equation was discretized into matrix form as follows

$$\mathbf{H}[\mathbf{A}]^{n+1}=\mathbf{G}\left[\frac{\partial\mathbf{A}}{\partial n}\right]^{n+1} \tag{3}$$

where **H** and **G** are the influence matrices. After a left multiplication of $\mathbf{SG}^{-1}$, Eq. (3) is added to Eq. (2), yielding the following set of equations

$$\left(\mathbf{K}+\frac{\mathbf{M}}{\Delta t}+\mathbf{SG}^{-1}\mathbf{H}\right)\cdot[\mathbf{A}]^{n+1}=\frac{\mathbf{M}}{\Delta t}\cdot[\mathbf{A}]^{n}-\mathbf{P}\cdot[\varphi]^{n+1} \tag{4}$$

2.3. Thermal diffusion equation

Under the assumption of energy balance, a 3D form of the thermal diffusion equation was deduced in a moving coordinate system

$$\rho c\frac{\mathrm{D}T}{\mathrm{D}t}-\nabla\cdot(\kappa\nabla T)=\dot{Q} \tag{5}$$

where T, ρ, c and κ are temperature, solid density, specific heat and thermal conductivity, respectively; and $\dot{Q}$ is the heat load generated in the conductor due to ohmic heating. $\dot{Q}$ can be expressed as

$$\dot{Q}=\frac{\vec{J}\cdot\vec{J}}{\sigma} \tag{6}$$

where $\vec{J}$ is the current density which can be expressed by

$$\vec{J}=-\sigma\left(\frac{\mathrm{D}\vec{A}}{\mathrm{D}t}+\nabla\phi\right) \tag{7}$$

In the temperature field calculation, a sparse symmetric matrix was generated by a finite element method based on the Galerkin form of weighted residuals.

2.4. Structural equation

Only the elastic processes of the armature and rails were considered to facilitate the coupling calculation. The governing equations based on conservation of momentum are expressed in the form of tensor as

$$s_{ij,j}+f_i=\rho\ddot{u}_i \tag{8}$$

where s, f and u are stress tensor, force per unit volume and structural displacement, respectively. The Galerkin method was used to discretize the structural equations to the finite element formulas which are expressed as follows

$$\mathbf{M}\left\{\frac{\mathrm{d}^2\mathbf{u}}{\mathrm{d}t}\right\}+\mathbf{K}\cdot\{\mathbf{u}\}=\{\mathbf{F}(t)\} \tag{9}$$

where **M** and **K** are mass matrix and stiffness matrix, respectively; and **F** is force vector that can be obtained from electromagnetic field. The time-dependent Lorentz force density is described as

$$\vec{F}=\vec{J}\times\vec{B} \tag{10}$$

where $\vec{B}$ is the magnetic flux density which can be expressed as

$$\vec{B}=\nabla\times\vec{A} \tag{11}$$

2.5. Numerical method

The electromagnetic and thermal fields were expressed by diffusion equations. The computational domain was discretized using the Galerkin method, and the time derivative terms were approximated by a backward difference scheme which is unconditionally stable. Same integration time step was chosen for solving the electromagnetic and thermal equations. The linear algebraic equations of the electromagnetic and thermal fields were solved by a preconditioned generalized conjugate residual (GCR) method [7] and an incomplete Cholesky conjugate gradient (ICCG) method [8], respectively.

The structural field was described by the dynamic equations with second-order derivative terms of the time. Due to the flexibility of LS-DYNA in explicit dynamics calculation and its extensive application in ballistics research [9], LS-DYNA was used as a solver for the structural equations. Although the characteristic time scale of structural field are quite different from that of other physical fields, the time step was controlled automatically in LS-DYNA.