Numerical Optimization of Electromagnet Current Distribution in Superconducting Linear Acceleration System  
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I. INTRODUCTION

Background

Conventional systems, a pneumatic pellet and a centrifugal pellet injections, inject ice pellets of frozen hydrogen gas into the fusion reactor at the velocity of 1-1.5 km/s.

In order to inject the ice pellets into the plasma core, Yanagi et al. recently propose a novel pellet injection system. This system electromagnetically accelerates the ice pellets on the magnetic levitation train. They adopt two types of high-temperature superconducting (HTS) film for acceleration and levitation.

⇒ They estimate 5-10 km/s as the velocity of the pellet injection.

Purpose

(1) We implement the NSGA-II non-dominated sorting genetic algorithm II of the multi-objective optimization in the FEM code for analyzing the shielding current density in an HTS film.

(2) We improve the pellet speed by using the NGnet (normalized Gaussian network) method as the shape optimization of current distribution in the electromagnet.

II. GOVERNING EQUATION AND EQUATION OF MOTION

Shielding Current Density in HTS Sample

\[ j = (2/\pi) \nabla \times \nabla \times \rho \times c \]  

Here, \( \rho \): scalar function, \( c \): thickness.

Integro-Differential Equations

\[ \frac{\partial}{\partial t} \int_{B} j(r',t)S(r,t)dr' + \frac{2}{\mu_0} \oint_{S} = - \frac{\partial}{\partial r}(B_r) - \frac{1}{\mu_0} \frac{\partial}{\partial r}(E_r) \]  

Here, \( B \): applied magnetic field by an electromagnet, \( S \): average operator over the HTS thickness, \( E \): electric field.

J-Constitutive Equation (Power Law)

\[ E = E(j, j_c) \frac{f(j)}{f(j_c)} \]  

Here, \( j_c \): critical current density, \( E_c \): critical electric field, \( N \): index.

Newton's law of motion

\[ \frac{dx}{dt}^2 = \frac{4e^2}{m} \frac{\partial}{\partial r} B(r) \times dr. \]  

Here, \( m \): total mass of the pellet container. \( B(r, z) \): r-component of an applied magnetic flux density \( B \).

Initial and Boundary Conditions

\[ S(r, 0) = S = 0 \quad \text{at} \quad t = 0 \]  

\[ Z = Z_0 \quad \text{at} \quad t = 0 \]  

Objectives functions

\[ \text{Maximize : } f_1(x) = \frac{v_f(x)}{v_{f_h}} \]  

\[ \text{Maximize : } f_2(x) = \frac{U_{\text{max}}(x)}{U_{\text{max}}(x)} \]  

Here, \( v_f \): the final velocity for the optimization, \( v_{f_h} \): the final velocity for the homogeneous current distribution, \( U_{\text{max}} \): the output energy for the SLA system, \( U_n \): the input energy for the SLA system.

Parameters

\( R = 5 \text{ cm}, b = 1 \text{ mm}, m = 10 \text{ g}, Z_0 = 1 \text{ mm}, N = 20, R_1 = 5 \text{ cm}, R_2 = 7 \text{ cm}, L = 10 \text{ cm}, E = 1 \text{ mV/m}, j_c = 1 \text{ MA/cm}^2, n = 101. \)

III. SIMULATION OF SLA SYSTEM

Filaments

Electromagnet

Schematic view of the electromagnet cross-section. Here, \( \cdot \): on-state, \( \cdot \): off-state. In addition, the on/off states in the number \( K \) of the filaments:

\[ x_j \equiv \begin{cases} 1 & (\Omega_j : \text{on-state}) \\ 0 & (\Omega_j : \text{off-state}) \end{cases} \quad (j = 1, 2, \ldots, K) \]  

Currents

\[ I_j(t, Z) = \frac{\alpha(t)}{\Omega_j} \left\{ \begin{array}{ll} g(t) & (0 \leq Z \leq Z_j) \\ 0 & (\text{otherwise}) \end{array} \right\} \quad (j = 1, 2, \ldots, K) \]  

Here, \( g \): the increasing rate of the current, \( Z \): the limit of acceleration range.

NGnet Method

\[ \Omega_j = \begin{cases} \text{on} & (g(t) \geq 0) \\ \text{off} & (g(t) < 0) \end{cases} \quad (j = 1, 2, \ldots, K) \]  

\[ g(y) = \sum_{j=1}^{M} \omega_j f_j(y) \]  

\[ b_j(y) = G_j(y) / \sum_{j=1}^{M} G_j(y) \]  

\[ G_j(y) = \frac{1}{2 \sigma^2} \exp \left\{ -\frac{|y - \mu_j|^2}{2 \sigma^2} \right\} \]  

Here, \( \sigma \): the positive constant value, \( \mu_j \): the center position of the jth filament, \( M \): the number of the 2D Gaussian function \( G_j \).

IV. CONCLUSION

By using the NGnet method and the NSGA-II, the shape optimization of the electromagnet can be obtained.

(1) The pellet speed increases significantly compared with the use of the homogeneous current distribution in the magnet.

(2) The applied magnetic flux density becomes the maximum at the edge (\( z = L/2 \)) of the magnet without depending on the shape of the magnet.

(3) The pellet speed and the energy efficiency are a trade-off relation.