Application of 3D Eddy Current Analysis on Magnetically Levitated Vehicles

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Abstract - **The eddy currents induced on the super conducting magnet (SCM) vessels of magnetically levitated vehicles (MAGLEV) have been analyzed. A 3D eddy current analysis code, based on a finite element method with thin shell approximation, is developed and verified through a mock-up SCM experiment. Through a coupled electromagnetic and mechanical analysis under SCM vibration, a SCM structure with low resistivity material coating on the inner vessel of SCM is found to be suitable for the significant reduction of helium evaporation due to eddy current loss.**

I. INTRODUTION

Magnetically levitated vehicles (MAGLEV) are planned for the next generation of high-speed mass transport train systems[1]. They levitate through the interaction of super conducting magnets (SCMs) with the induced magnetic field of figure-eight passive coils placed on the tracks, as shown in Fig.1. The SCM system is composed of the vaccum vessel, the radiation shield, and the helium (He) container.

Large amounts of eddy currents are induced on these parts due to the ripple field generated by the passive coils. Strong vibrations are also induced through the **JxB** force of the eddy currents and superconducting magnetic field. The vibrations induce secondary eddy currents on the inner portions which are kept at liquid He temperature.

In order to reduce the weight of the SCM system, designs have used an SCM coil with a low amount of stabilizing copper, a vacuum vessel with aluminum alloy, and a compact He refrigerator with small capacity. These designs tend to reduce SCM reliability because of the reduced margin for coil quenching and larger eddy current heating loss on areas at low He temperature. Therefore, accurate prediction of the eddy current behavior is very important for reliable SCM design.

In this study, we present a 3D eddy current simulation applied to the complicated SCM structures. A 3D eddy current analysis code, based on the finite element method, was developed [2] and confirmed through a mock-up SCM experiment. The electromagnetic force due to eddy currents was comparable to the mechanical force of structural deformation. Therefore, we present a simple coupled analysis of electromagnetic and mechanical forces assuming rigid body displacement of SCM components. We show the fundamental principle for the reduction of eddy current loss through this coupled analysis.

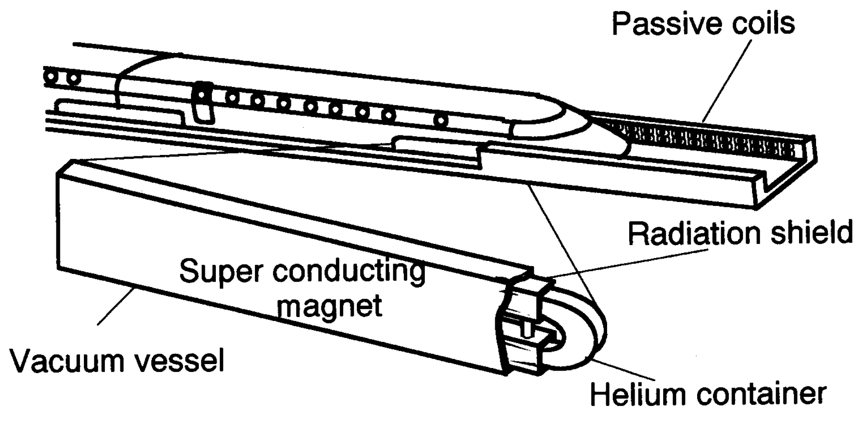

Fig. 1 Concept of MAGLEV and super conducting magnets

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II. 3D EDDY CURRENT ANALYSIS CODE

Considering that the SCM is composed of thin shell vessels made of non-magnetic materials, we can simplify the basic equation. The eddy current code developed here is based on the integral equation with current vector potentials on the shell conductors as unknowns. The basic equation is [2-4]:

$$\frac{\mu_0}{4\pi}\frac{\partial}{\partial t}\int\frac{\mathbf{J}\cdot\mathbf{J}'}{|\mathbf{r}-\mathbf{r}'|}\,d\mathbf{r}\,d\mathbf{r}' + \frac{1}{\sigma}\int \mathbf{J}^2 d\mathbf{r} + \int \mathbf{J}\cdot\dot{\mathbf{A}}_{ex}\,d\mathbf{r} = 0 \quad (1)$$

where $\mathbf{J}$ and $\mathbf{A}_{ex}$ are the shell surface eddy current density and the magnetic vector potential of external source, and μ_0 and σ are the vacuum permeability and the conductivity of materials in SCM. Eq.(1) presents a conservation of magnetic energy stored in the system. For the eddy current simulation due to the ripple field of the passive coils, the external source $\mathbf{A}_{ex}$ is

$$\mathbf{A}_{ex}(\mathbf{r}, t) = \sum_n \mathbf{A}_n(\mathbf{r}) \exp[\,j\,(\omega_n t - k_n z)] \quad (2)$$

namely the field is the superposition of harmonics of traveling waves. For the eddy current simulation due to structural vibration, the external source $\mathbf{A}_{ex}$ is evaluated as

$$\mathbf{A}_{ex}(\mathbf{r}, t) = \left(\frac{\partial \mathbf{A}_{sc}}{\partial \mathbf{x}}\right)\mathbf{x}(\mathbf{r}, t) \quad (3)$$

where $\mathbf{A}_{sc}$ and $\mathbf{x}$ are the vector potential of the superconducting static field and the displacement of the structures. In Eq.(1), the eddy current $\mathbf{J}$ is presented by a normal component of current vector potential T_n as,

$$\mathbf{J} = \nabla T_n \times \mathbf{n} \quad (4)$$

whrer $\mathbf{n}$ is the unit vector normal to the surface. Descretizing the conductor surfaces into triangular elements, we obtain the matrix equation on the current vector potentials T_n and the displacement x_n on each node n as,

$$M\dot{T} + RT = \left(\frac{\partial \phi_{sc}}{\partial \mathbf{x}}\right)\dot{X} \quad (5)$$

where $T=\{T_n\}$, $X=\{x_n\}$, ϕ_{sc} is the magnetic flux due to SCM currents, and M and R are the matrices corresponding to inductance and resistance.

In a typical simulation, the vacuum vessel, shield, and He container of SCM are descretized into 6000 elements. Typical CPU time is 10 min using the super computer HITAC S820.

III. COMPARISON WITH MOCK-UP EXPERIMENT

The mock-up SCM and its experimental set-up are shown in Fig.2. The passive coil driven by a three-phase variable frequency generator generates a traveling wave field in the mock-up SCM. The radiation shield and He container are cooled down by liquid nitrogen. Magnetic fields are measured by search coils placed on the surfaces of each component. Figure 3 shows a comparison of some typical measured and calculated results. The measurement point is indicated in Fig. 2. The measured and calculated values agree within 20 % in average, although the measured values on the radiation shield is scattered due to unidentified reason.

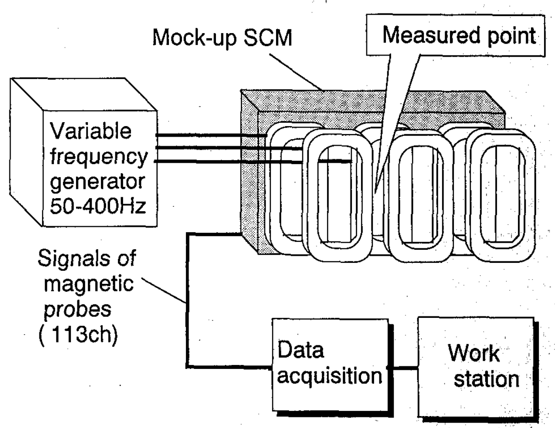

Fig.2 Experimental set up

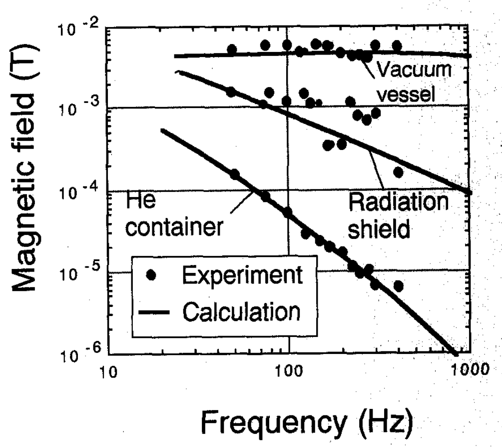

Fig. 3 Comparison of calculated and experimental resuls on mock-up experiment

IV. ANALYSIS ON CURRENT SCM DESIGN

Eddy currents are simulated for the current design of the SCM which is being developed for use of the new Yamanashi experimental line. At first, the eddy currents due to the ripple field of passive coils are analyzed. As shown in Fig.4, the eddy patterns reflecting the field pattern of the figure-eight passive coils sweep from the left to the right hand side of the SCM vessels. The eddy current Joule loss due to the ripple field is 400 W in the vacuum vessel at the train velocity of 500 km/h. On the radiation shield, the Joule loss is reduced to 2 W, since the ripple magnetic field is shielded by the vacuum vessel. Further, the joule loss on the He-container is 10 mW, which is much less than the design limit of 1 W.

On the other hand, the eddy current loss due to structural vibrations on the He-container is fairly large. Figure 5 shows the eddy current pattern during the yawing vibration between the radiation shield and He-container, which is one of the probable eigen modes of structural vibrations. The Joule loss on the He container reaches 3 W with only a 20 μm displacement. In this case, the equivalent stiffness of the electromagnetic force for a given displacement becomes comparable to the mechanical stiffness. Assuming a rigid body displacement, a coupled analysis of the electromagnetic force and structure is performed. The equation for mechanical displacement

$$M_m\ddot{\mathbf{X}} + K\mathbf{X} + \left(\frac{\partial \phi_{sc}}{\partial \mathbf{X}}\right) \mathbf{T} = 0 \tag{6}$$

is coupled with Eqs. (5) , where M_m and K are the equivalent mass and stiffness of the radiation shield and the He container system. The third term presents the electromagnetic force due to eddy currents. Equations (5) and (6) presents the closed coupled system for eddy currents $\mathbf{T}$ and displacement $\mathbf{X}$.

Figure 6 shows results of coupled analysis. The frequency responses of (a) displacement with and without coupling consideration, (b) eddy current for a unit displacement for various He container resistivities, and (c) the Joule loss on the He container for various resistivities are shown. In case of 'without coupling', ϕ_{sc} is forced to zero. It can be seen from Fig. 6(a) that, above the threshold frequency f_{th}, which is the inverse of the equivalent L/R time of the eddy current, the coupled effect becomes dominant and the displacement is suppressed by a factor of 5. As a result, the Joule loss shown in Fig. 6(c) can be reduced if the resistivity of the He container is reduced. Coating the He container, made of stainless steel, with low resistivity materials such as Cu or Al is effective for Joule loss reduction. A detailed simulation shows that the Joule loss can be suppressed below 0.2 W by a such coating, which is 1/15 of that of the conventional He container.

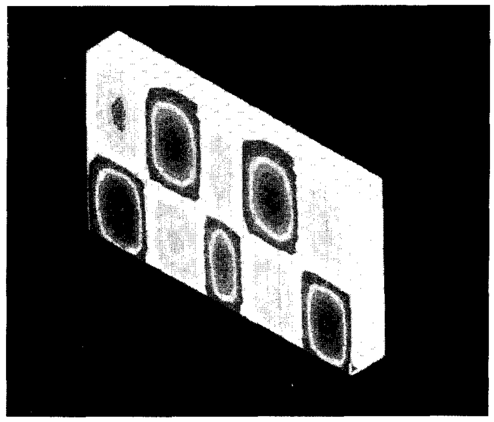

Fig. 4 Eddy current pattern on the vacuum vessel under the influence of passive coil magnetic field

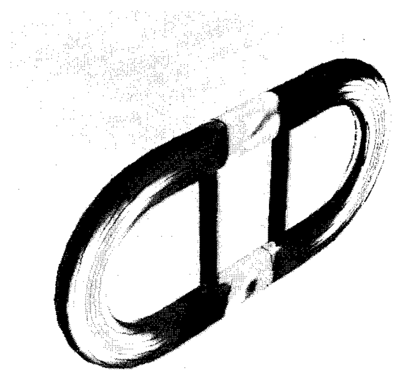

Fig. 5 Eddy current pattern on the He container during yawing vibration of the radiation shield

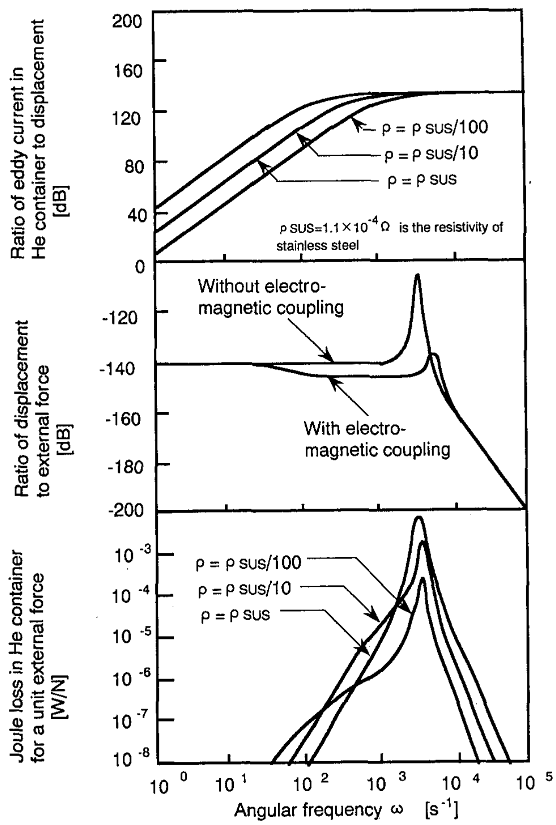

Fig. 6 Characteristics of electromagnetic and structural coupled system

V. CONCLUSION

In conclusion, a thin shell approximated 3-D eddy current code was found to be suitable for evaluation of joule loss on the SCM structure. Through a simple coupled analysis between electromagnetic and mechanical forces, coating with low resistivity material on the He container was found to be effective for reduction of eddy current joule loss.

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