

Temperature-Dependent Damping Performance in a Multi-DOF Eddy Current Damper for Cryogenic Applications

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Eddy current dampers utilize electromagnetic forces generated by eddy currents in a conductor moving through a magnetic field. This design eliminates mechanical contact, offering durability and long service life. However, the damping performance is typically lower than that of rubber, oil, or friction dampers. Moreover, high-conductivity materials exacerbate the skin effect, leading to increased magnetic stiffness and reduced damping efficiency. This study investigates these challenges by analyzing the performance of eddy current dampers using materials with different electrical conductivities. The evaluations were conducted under room temperature and cryogenic conditions using two-dimensional finite element analysis. The results highlight the influence of electrical conductivity and temperature on damping performance and magnetic stiffness.

Index Terms—Eddy current dampers, Rotating machines, multiple-degree-of-freedom vibrations, cryogenics.

I. INTRODUCTION

An eddy current damper (ECD) is a non-contact vibration suppression device that utilizes the electromagnetic force generated by eddy currents induced when a conductor moves relative to a magnetic field [1]-[2]. Owing to its wear-free and lubricant-free nature, ECDs offer the advantages of long service life and suitability for cryogenic environments. However, their damping performance is often inferior to traditional friction-based wire mesh dampers used in cryogenic environments.

The damping performance of ECDs depends on the magnitude of eddy currents, leading to the use of high-purity aluminum (A1070) with high electrical conductivity [3]. However, significant skin effects in such materials were found to reduce performance.

This study addresses this limitation by using an aluminum alloy (A7075) with lower electrical conductivity and implementing a design to reduce magnetic stiffness. Finite element analysis (FEA) was conducted to evaluate the impact of these changes on damping performance, and the results are discussed.

II. EDDY CURRENT DAMPER

The structure of the proposed eddy current damper shown in Fig. 1(a) is designed to suppress axial and radial translational vibrations of a rotating shaft without interfering with its rotational motion. The damper is mounted on the shaft via bearings, allowing for independent rotational movement. The mover consists of two radially extending discs, fabricated from either high-purity aluminum (A1070) or aluminum alloy (A7075) to enable a performance comparison based on electrical conductivity.

Samarium-cobalt magnets (Recoma 33E, Arnold Magnetic Technologies) were employed due to their low temperature dependence in magnetic properties. The magnetic flux density distribution of the damper's cross-section is shown in Fig. 1(b). The magnet arrangement utilizes two distinct magnetic circuits:

a short-circuited magnetic path between adjacent magnets and a magnetic circuit through a SUY-1 soft magnetic yoke.

The short-circuited magnetic path predominantly generates damping forces in the direction perpendicular to the magnet surface. Conversely, the magnetic circuit through the yoke is primarily responsible for damping forces parallel to the magnet surface.

III. ANALYSIS CONDITIONS

The performance of the proposed damper was evaluated under two temperature conditions: 20 degrees Celsius, representing room temperature, and minus 190 degrees Celsius, simulating a liquid nitrogen environment. These evaluations were conducted using two-dimensional finite element analysis with Simcenter™ MagNet™ (Siemens Digital Industries Software). Only the electromagnetic field was analyzed, and the

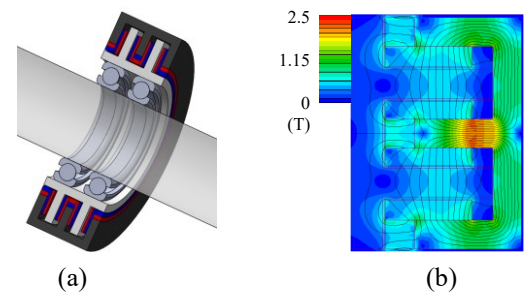


Fig. 1. The proposed eddy current damper. (a) 3D view. (b) Magnetic flux density distribution of cross-sectional model.

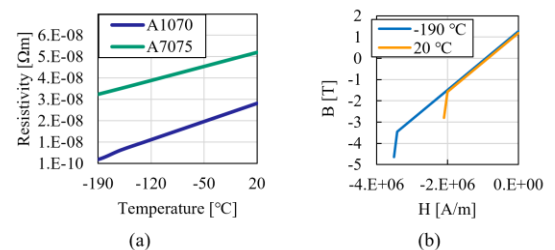


Fig. 2 Material properties used in the analysis. (a) Temperature dependence of electrical resistivity. (b) B-H curves of the samarium-cobalt magnet.

effect of temperature was incorporated by adjusting the material's electrical resistivity according to temperature-dependent properties. The temperature-dependent electrical resistivity of the materials and the B-H curves of the samarium-cobalt magnet used in the analysis are shown in Fig. 2. These properties were incorporated into the electromagnetic simulation model. In the simulation model, a spring was attached to the mover of the damper to approximate it as a single-degree-of-freedom (SDOF) spring-mass-damper system.

To evaluate the damping performance in both axial and radial directions, initial velocity was applied in each direction during the simulations. The resulting damping waveforms were fitted using the least squares method based on the following equation:

$$\begin{aligned} X(t) &= x_{over}(t) + x_{under}(t) \\ &= \frac{v_0}{2\omega_1\sqrt{\zeta_1^2-1}} \exp(-\zeta_1\omega_1 t) \\ &\quad \times \left\{ \exp\left(\sqrt{\zeta_1^2-1}\omega_1 t\right) - \exp\left(-\sqrt{\zeta_1^2-1}\omega_1 t\right) \right\} \\ &\quad + \frac{v_0}{\omega_2\sqrt{1-\zeta_2^2}} \exp(-\zeta_2\omega_2 t) \sin\left(\omega_2\sqrt{1-\zeta_2^2}t\right) \end{aligned} \quad (1)$$

which represent the superposed theoretical response of an SDOF spring-mass-damper system. Here, x_{over} and x_{under} are the theoretical equations for a single-degree-of-freedom spring-mass-damper system, and v_0 is the initial velocity. The variables are $\zeta_1, \omega_1, \zeta_2, \omega_2$, where ζ is the damping ratio and ω is the natural frequency.

IV. ANALYSIS RESULT AND DISCUSSION

The results of the analysis indicate a significant influence of electrical conductivity on the damping performance of the damper. Fig. 3 illustrates the damping waveforms, showing that vibrations attenuate the fastest in both axial and radial directions when A1070 is used at -190 °C.

The damping coefficients derived through curve fitting are presented in Fig. 4. For the same material, the damping coefficients increase with increasing electrical conductivity as the temperature decreases, due to the increased eddy currents that generate stronger electromagnetic forces. However, A7075 at -190 °C exhibits a slightly lower electrical conductivity compared to A1070 at 20 °C, yet demonstrates a higher damping coefficient in axial direction. This is likely due to the improved magnetic properties at lower temperatures.

Fig. 5 shows the magnetic stiffness values calculated by subtracting the attached spring stiffness from the stiffness derived from the natural frequencies. Notably, the magnetic stiffness of A1070 at -190 °C is substantially higher than it is at 20 °C. This behavior can be explained by the skin effect, which is described by the following equation:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad (2)$$

In this equation, δ represents the skin depth, defined as the distance from the conductor surface where the current amplitude reduces to $1/e$ and the phase delays by 90 degrees. The parameters ω, μ , and σ refer to the frequency of magnetic field variation, the permeability of the conductor, and the

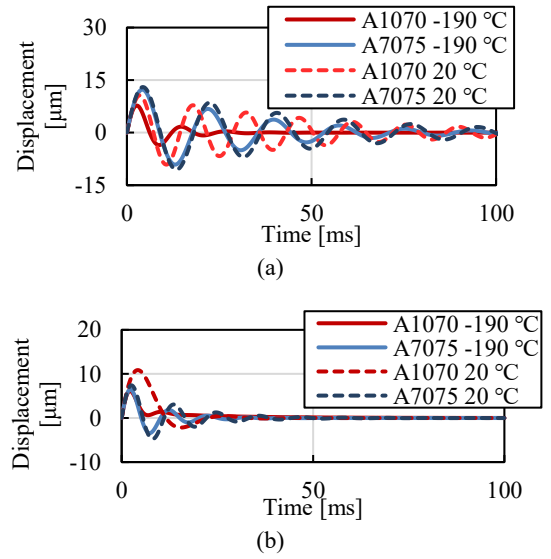


Fig. 3. Time responses of displacement. (a) Axial direction (b) Radial direction

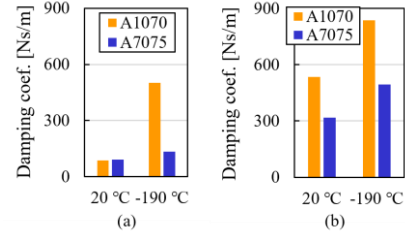


Fig. 4. Damping coefficients in axial and radial directions. (a) Axial. (b) Radial.

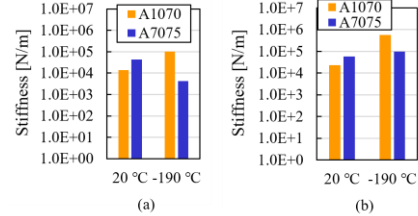


Fig. 5. Magnetic stiffness of each direction. (a) Axial. (b) Radial.

electrical conductivity of the conductor, respectively. An increase in electrical conductivity leads to greater phase delay in the current, thereby contributing to work as a spring-like component. This phenomenon accounts for the exceptionally high magnetic stiffness observed for A1070. These findings underscore the critical role of electrical conductivity and temperature in optimizing the design and material selection of eddy current dampers.

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