1. Global Logistics Paradigm Shift and Technical Requirements

The global logistics sector is undergoing a profound paradigm shift driven by the mandate to achieve a net-zero carbon footprint by 2050. This environmental directive has accelerated the electrification of industrial machinery, resulting in an unprecedented demand for automated, large-scale warehouse solutions and high-capacity logistics robots capable of handling payloads exceeding 2 tons. In these heavy-duty robotic platforms, sophisticated braking architectures are critical to ensuring both operational efficiency and human safety. While regenerative braking manages routine deceleration, power-off electromagnetic brakes function as a vital fail-safe mechanism, providing essential positional holding and emergency stopping capabilities.

2. Problem Statement and Research Objective

Despite the critical role of power-off electromagnetic brakes, their technical stability and vibrational reliability under high-load conditions have remained relatively underexplored. This study investigates the frictional vibration behavior of electromagnetic brakes specifically designed for high-load logistics applications. To elucidate the underlying mechanisms of vibrational instability, a numerical investigation was conducted utilizing the commercial finite element analysis software, Abaqus.

3. Research Content

In this study, a Complex Eigenvalue Analysis (CEA) was performed to investigate the instability behavior of the system under varying friction coefficients. The analytical procedure was executed through the following structured phases:

1. **Design and Assembly:** Deviating from conventional electromagnetic braking architectures, a novel electromagnetic braking mechanism was developed by adapting principles from automotive braking systems.
2. **Vibrational Stability Analysis with Respect to Geometric Friction Patterns:** The brake pads are positioned symmetrically on the upper and lower sides of the rotating disc, utilizing a configuration of four segmented pads on each side. Depending on the assembly orientation of these four pads, the configuration is classified into either a symmetric or an asymmetric contact pattern. While this geometric variance does not inherently alter the magnitude of the friction force, it induces critical shifts in the localized pressure distribution, the center of action of the frictional forces, the azimuthal contact area relative to the rotational axis, and the geometric stiffness. Consequently, these structural modifications shift the natural frequencies of the system, thereby exercising a direct influence on its overall vibrational stability.

4. Conclusion

It was identified that the primary cause of most instability modes is the bending modes occurring in the circular assembly components, namely the cover, disc, and armature.

In the symmetric pad pattern, the modes exhibiting instability are distributed over a wider frequency range compared to the asymmetric pad pattern.

The primary instability mode was observed in the 10 kHz frequency band with high real values, which was mainly attributed to the mode coupling between the doublet modes of the disc.

The frequency split in the disc's doublet modes is considered to be caused by the asymmetry arising from the hub key connection and the bolt-fastening areas.

Future braking tests will be conducted to validate the correlation between the analysis and experimental results.