

## **Countermeasures for Friction-Induced Vibration in Pantographs Using Modal Coupling Strength Analysis**

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This study investigates friction-induced unstable vibrations in railway pantographs through modal coupling analysis. A flexible multibody dynamics model was developed to examine the effect of sliding friction on natural modes. Coupling strength was introduced as a quantitative measure. The results showed that under knuckle-backward conditions, increasing friction narrows the frequency gap between the first and fourth modes, causing instability above a friction coefficient of 0.79. Parametric studies revealed that reducing plate spring stiffness weakens coupling and suppresses vibrations. Hammering tests and modal analysis confirmed the validity of the simulations, showing that reducing the thickness of plate springs decreases coupling strength and mitigates instability.