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Stochastic Rigid-Flexible Coupling Dynamics and Nonlinear Contact Analysis of Sounding Rocket Launch Dispersion

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The trajectory dispersion of unguided sounding rockets is predominantly governed by the vehicle's state vector at the instant of launcher separation. Traditional dispersion analyses typically decouple the launcher structural dynamics from the vehicle's equations of motion, modeling the guide rail as a static Euler-Bernoulli beam subject to quasi-static loading. Such deterministic simplifications fail to capture the transient vibro-impact responses induced by the accelerating moving mass and the geometric nonlinearities arising from mechanical clearances. This study establishes a high-fidelity computational framework for the stochastic assessment of launch dispersion by integrating flexible multibody dynamics with a dissipative continuous contact model. We formulate the guide rail as a continuum deformable body using the Floating Frame of Reference (FFR) formulation, employing Component Mode Synthesis to capture the inertia coupling between rigid-body motion and elastic deformation. The tribological interface between the launch lugs and the rail is modeled using the Lankarani-Nikravesh contact force model, explicitly accounting for clearance-induced chaotic motion and hysteresis damping. A Monte Carlo simulation framework is implemented to propagate aleatory uncertainties in thrust misalignment, initial rail straightness, and wind loading through the nonlinear system. Numerical results demonstrate that the coupling of the time-varying rocket mass with the rail's eigenmodes produces a significant "whip effect" at separation, where the tip-off angular rate is statistically dependent on the phase angle of the rail's vibration. The study concludes that joint clearances act as a nonlinear filter, attenuating high-frequency disturbances while potentially amplifying lower-frequency structural modes under resonance conditions.

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