Physical Analysis of the Rotating Saddle Trap: The Mechanical Analogue of the Quadrupole Ion Trap

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The quadrupole ion trap utilizes time-varying electric fields to confine ions for high precision atomic measurements. To explain its working principles, the rotating saddle trap was used as a mechanical analogue, illustrating how a time-varying saddle-shaped potential can trap particles. This project investigated the stability and dynamics of a ball on a rotating saddle and the extent to which the analogy between the two traps can be drawn. 3D printed saddle surfaces mounted on a turntable were used to experimentally record the ball's trajectory and lifetime. A simplified analytic model predicted that the ball is indefinitely stable and oscillates with two frequencies in the rotating frame of the saddle if the saddle attains a sufficiently high angular velocity. This result is qualitatively similar to that of quadrupole ion traps. However, experimental results showed how the analytic model could not properly account for finite ball lifetimes and numerical values of the two observed oscillation frequencies. A numerical model that more accurately took into account the ball's rotation reconciled with experiments and thus had more predictive power over the analytic model. Yet, the rotating saddle serves as an intuitive analogue due to qualitative similarities between the two traps. Furthermore, slipping was proven by the numerical model to destabilize the ball and result in finite ball lifetimes, further limiting the aforementioned analogy. This demonstrates the power and limitations of analogies in physics and opens interesting questions for research in chaotic dynamics. These governing equations can be similarly applied to other systems with objects rolling on moving surfaces found in industrial machinery.