

Theoretical and Experimental Analysis of Propellantless Propulsion Using Resonant Cavity Interactions, Quantum Field Effects, and Advanced Optimization

Abstract—This paper presents a comprehensive theoretical and experimental analysis of a propellantless propulsion system that harnesses asymmetric resonant cavities to interact with the quantum vacuum, potentially generating net thrust without ejecting reaction mass. By extending classical Maxwellian waveguide theory to include Casimir-like and Unruh-type vacuum effects, we describe how carefully engineered high-Q cavities—especially those with non-symmetric boundaries—can exhibit measurable forces. Building on Charles Buhler’s patented approach (WO2020159603A2), we introduce geometric, material, and dynamic design optimizations that could enhance thrust. Experimental results from vacuum-chamber torsion pendulum tests suggest the presence of small, potentially significant forces, though further validation is needed. We explore systematic protocols, error mitigation strategies, and advanced modeling requirements. Future applications in satellite station-keeping, deep-space exploration, and fundamental physics are also discussed.

Index Terms—Propellantless Propulsion, Resonant Cavity Interactions, Quantum Field Interactions

I. INTRODUCTION

A propulsion system that does not rely on mass reaction has transformative implications for space travel and satellite technology. Traditional chemical, electric, or ion thrusters must carry propellant, limiting mission duration and total Δv . A system that apparently breaks the rocket equation—if validated—could enable extended missions, smaller launch masses, and new forms of maneuvering in orbit.

In this context, Charles Buhler’s resonant-cavity propulsion concept (WO2020159603A2) seeks to generate thrust from internal electromagnetic fields, leveraging asymmetric boundary conditions and quantum vacuum fluctuations. While these ideas challenge conventional interpretations of momentum conservation in closed systems, proponents argue that momentum exchange could occur with the external field or vacuum itself.

This article provides an integrated framework for resonant-cavity propulsion, explaining the Maxwell stress tensor approach, quantum vacuum theories, and their adaptation to tapered or asymmetric waveguides. We then expand on technological optimizations—including novel geometrical configurations,

material enhancements, high-power RF, and dynamic boundary control—that could increase the magnitude and stability of any net force.

II. THEORETICAL FRAMEWORK

A. Electromagnetic Resonance in Asymmetric Cavities

At the core of this technology is a metallic, high-Q resonant cavity driven by RF or microwave power (ranging from hundreds of MHz to a few GHz). Maxwell’s equations in source-free regions can be written as:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (1)$$

$$\nabla \times \mathbf{H} = \varepsilon \frac{\partial \mathbf{E}}{\partial t}, \quad (2)$$

with boundary conditions enforcing $\mathbf{E}_{\parallel} = 0$ (or $\mathbf{H}_{\perp} = 0$) on perfectly conducting walls. In a tapered or conical cavity, the standing-wave pattern is non-uniform, and the Maxwell stress tensor may yield a small net force:

$$\mathbf{T} = \varepsilon_0 \left(\mathbf{E}\mathbf{E} - \frac{1}{2}E^2\mathbf{I} \right) + \mu_0 \left(\mathbf{H}\mathbf{H} - \frac{1}{2}H^2\mathbf{I} \right). \quad (3)$$

If the field geometry inside the cavity is sufficiently asymmetric, integrating \mathbf{T} over the inner surfaces can, under certain boundary conditions, produce a non-zero resultant:

$$\mathbf{F}_{\text{EM}} = -\int_S \mathbf{T} \cdot \mathbf{n} dA. \quad (4)$$

For example, a conical cavity with a 5:1 diameter ratio driven at 2.45 GHz may achieve electric field densities exceeding 10^5 V/m, potentially leading to an asymmetric force distribution.

Though classical electrodynamics typically predicts no net thrust in a closed, rigid cavity, subtle asymmetries or boundary-condition changes could disrupt the usual symmetry and allow a minute net force.

B. Quantum Vacuum Contributions

1) *Casimir-Like Interactions*: In parallel plate geometries, the Casimir effect arises from vacuum mode exclusion, causing an attractive force between the plates. For resonant cavities with more complex shapes (truncated cones, etc.), the net Casimir energy can have non-trivial spatial gradients, potentially yielding small lateral or axial forces. While weak on macroscopic scales, the extremely high electromagnetic field densities in high-Q cavities may magnify such effects.

2) *Dynamical Vacuum Effects*: Unruh-like radiation and the dynamical Casimir effect arise when boundary conditions change in time or the cavity undergoes acceleration, effectively exciting quantum vacuum modes. While direct observation of these effects is challenging, they provide a theoretical mechanism for how a cavity might exchange momentum with the vacuum, generating measurable thrust under certain resonant or transient conditions.

III. CAVITY GEOMETRY, MATERIALS, AND POWER SYSTEM

A. Tapered and Multi-Stage Designs

Buhler's patent and related concepts often feature:

- **Truncated Conical Cavity**: One circular opening larger than the other, ensuring asymmetric field distribution.
- **Compound Cavities**: Multiple sections or modes coupled in series to amplify internal standing waves or to produce complex boundary interactions.
- **Phase-Matched Arrays**: Tightly controlling multiple cavities in parallel to constructively reinforce wave patterns in targeted regions.

B. High-Performance Materials

- **Metals (Copper, Silver)**: Common choices for cavity walls due to high conductivity and ease of fabrication.
- **Superconductors**: Niobium or high-temperature superconductors, offering dramatically reduced surface losses—hence, higher stored energy and potentially larger net forces.
- **Metamaterials**: Engineered materials with exotic permittivity/permeability that can further tailor the electromagnetic field inside the cavity, intensifying asymmetry.

C. Microwave/RF Power Supply

Solid-state amplifiers, magnetrons, or klystrons can drive the cavity at its resonant frequency. Key considerations:

- **Power Level**: From a few watts to kilowatt-range, balancing the desire for higher field amplitudes with thermal limits and potential plasma formation.
- **Frequency Tuning**: Real-time matching to the cavity's resonant modes, often with phase-locked loops or network analyzers.
- **Pulsed vs. CW**: Pulsed operation can reach higher peak powers with less average heating, possibly enhancing transient vacuum effects.

IV. DYNAMIC OPTIMIZATION AND ADVANCED CONCEPTS

A. Time-Varying Boundaries

Actively modulating the cavity geometry or reflectivity can induce transient field distributions:

- **Piezoelectric or SMA Inserts**: Slightly deforming the cavity wall to shift resonance and excite different wave modes.
- **PIN Diodes or Varactors**: Embedded in the cavity walls to vary surface conductivity or boundary conditions at high speed, potentially tapping the dynamical Casimir effect.

B. Metamaterial Waveguides

Inserting gradient-index materials or negative-index metamaterials could manipulate the internal phase velocity of waves, supporting unusual mode patterns and further breaking field symmetry.

C. Thermal and Mechanical Stability

High field intensities can cause local heating, altering the cavity shape or the superconducting transition. Active cooling systems—water channels or cryogenic loops—mitigate these effects and maintain a stable resonance.

V. EXPERIMENTAL SETUP AND MEASUREMENT PROTOCOLS

A. Vacuum Chamber and Thrust Stand

All tests take place in a low-pressure environment ($< 10^{-5}$ torr) to minimize aerodynamic and ionic thrust artifacts. A torsion pendulum or low-noise thrust balance monitors forces in the micronewton-to-millinewton range.

B. Calibration and Systematic Error Control

- **Null Tests**: Replacing the asymmetric cavity with a dummy load or symmetrical cavity confirms baseline measurement noise.
- **RF Leakage Monitoring**: Shielding and near-field probes verify that external fields are not coupling to the thrust stand or chamber walls.
- **Thermal Drift**: Temperature sensors and real-time compensation algorithms account for small expansions of the cavity structure.

C. Multi-Axis Measurement

Using multi-axis force sensors or orthogonal thrust stands helps identify whether thrust is purely axial or includes lateral/torque components—a crucial step for verifying real net force rather than spurious electromagnetic interactions with the environment.

VI. RESULTS AND DISCUSSION

A. Preliminary Thrust Observations

Prototypes inspired by Buhler’s designs have repeatedly shown small thrust signals in the micronewton range exceeding typical measurement uncertainty, though reproducibility across different labs remains challenging. Some observations indicate that peak thrust occurs near specific resonant modes, suggesting that mode shape may contribute to potential momentum asymmetry. These preliminary findings require further refinement and replication to confirm their validity.

B. Comparison with Theoretical Models

Classical electromagnetic simulations (using FEM or FDTD methods) often predict negligible net force under strictly static conditions. However, incorporating dynamic boundary conditions or simplified vacuum fluctuation terms can yield small but non-zero thrust estimates. Key sources of discrepancy remain:

- Cavity Losses: Realistic conductivity vs. idealized perfect conductors.
- Complex Mode Interference: Interactions among multiple modes can be difficult to capture analytically.
- Vacuum Fluctuation Approximations: Precise quantum calculations are computationally intensive, necessitating approximate methods.

C. Potential Resonances and Frequency Tuning

Experiments suggest that thrust may vary with frequency, exhibiting peaks and nulls that imply specific mode structures are more conducive to net force generation. Tracking these variations—and their dependence on cavity geometry, temperature, or external fields—is a central research priority.

D. Future Optimization Studies

- Superconducting Cavities: Dramatically higher Q-factors might amplify small vacuum-fluctuation-driven effects.
- Phase-Locked Multi-Cavity Arrays: Could spatially concentrate or steer electromagnetic momentum flows.
- Dynamic Metamaterials: Time-varying permittivity within the cavity to explore direct coupling to Unruh-like phenomena.

VII. POTENTIAL APPLICATIONS

A. Satellite Station-Keeping and Attitude Control

If validated, even low-level thrust would enable long-duration orbital maneuvers without consuming fuel. This would significantly extend satellite lifespans and reduce launch mass.

B. Deep-Space Exploration

Continuous low-thrust acceleration could shorten travel times, provided the thrust-to-power ratio improves and can scale to higher levels.

C. Terrestrial Demonstrations

Testing these devices in air is complicated by ionization and electromagnetic interference. However, sealed demonstration platforms (enclosed in vacuum or partial vacuum) might offer limited near-Earth feasibility studies.

D. Fundamental Physics

Detailed measurements of these propulsion devices could reveal subtle quantum vacuum phenomena, informing our understanding of boundary-condition-driven field interactions and possibly uncovering new physics at the interface between classical and quantum theories.

VIII. ADVANCED DEVELOPMENT AND OPTIMIZATION STRATEGIES

Below is a concise summary of key optimization pathways to increase thrust and enhance reproducibility:

- 1) Multi-Stage or Compound Cavities: Coupled resonators with carefully controlled phase relationships.
- 2) Metamaterial Inserts: Tailored permittivity/permeability profiles to intensify field asymmetry.
- 3) Superconducting Walls: Achieve ultra-high Q-factors for maximal electromagnetic energy storage.
- 4) Dynamic Boundary Tuning: Leveraging piezoelectrics, diodes, or mechanical actuators for real-time control of cavity geometry and resonance conditions.
- 5) High-Fidelity Modeling: Combining electromagnetic full-wave simulations with approximate quantum field methods to better predict and refine design parameters.
- 6) Stringent Experimental Protocols: Multi-axis measurement, high vacuum, thorough shielding, and cross-lab replication to validate small force signals.

IX. CONCLUSION

This article synthesizes Charles Buhler’s resonant-cavity propulsion concept with broader developments in electromagnetic waveguide optimization and quantum vacuum physics. Although much debate surrounds the plausibility of propellantless thrust, repeated experimental hints justify continued rigorous investigation. Adopting advanced cavity designs, high-quality materials, and dynamic boundary control could enhance any existing effect, ultimately determining whether these forces are genuine or artifacts.

The potential impact on spaceflight, satellite longevity, and our fundamental grasp of vacuum-field interactions is profound. Ongoing collaboration among physicists, engineers, and materials scientists is essential to unravel the true capabilities—and limitations—of these unconventional thruster designs.

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