Measurement Error Analysis of Impulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum

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Kyle B. Flanagan, Peter C. Dohm
Prime Lightworks Inc., 2909 Oregon Ct Ste C12, Torrance, CA 90503 USA

Introduction:

Fully electric spacecraft propulsion without need for conventional mass propellant would provide a revolutionary step forward in space exploration and planetary science. Error analysis for measurements of impulsive thrust from closed radio-frequency (RF) cavities must be rigorous in light of apparent violations of momentum conservation. Prime Lightworks vacuum test campaign of 8-11GHz CubeSat RF cavity thrusters follows from and expands upon related efforts by Dr. Harold White of Eagleworks Laboratories Advanced Propulsion at NASA Johnson Space Center **[1]** and Prof. Martin Tajmar of Institute of Aerospace Engineering at Dresden University of Technology **[2]**.

Calibration/Control:

Calibrations and control tests indicate potential sources of test measurement error include changes in vacuum pressure during test, thermal expansion due to heating of electronics, and magnetic torque from interaction between currents on power cables and Earth magnetic field. To mitigate potential sources of test measurement error, Prime Lightworks impulsive thrust measurement apparatus includes a 50watt RF power electronics enclosure (<6U footprint), enclosed in magnetic shielding to mitigate interactions with Earth's magnetic field, which provides 8-11GHz RF power to a closed RF cavity thruster (<1U footprint) onboard a torsion pendulum in a vacuum chamber.

Test Methodology:

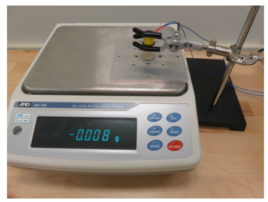
Position displacement measurements on the torsion pendulum are carried out using a laser interferometer through the vacuum chamber viewport. Combined use of eddy current damper, electromagnet pulse calibration, and magnetic shielding at suitably low vacuum pressure provides sufficiently low noise environment for measurements of thrust from closed RF cavity resonators with thrust-to-power ratios at or exceeding 1.2mN/kW.

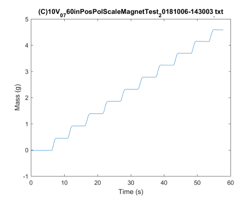
Discussion:

Prime Lightworks control tests identified 28μN thrust pulses in forward and reverse configurations (opposite pulse directions). Addition of magnetic shielding enclosure on power electrics subsystem decreased thrust pulses by an order of magnitude to less than 3μN. This demonstrates measurement error due to torque from interaction with Earth's magnetic field ($\tau = \mu \times B$).

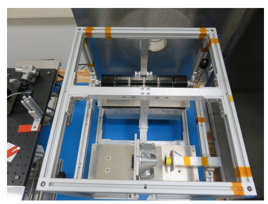
Calibration Results:

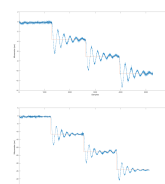
Prime Lightworks has completed measurements of calibration ratios between pendulum displacement and applied force. Calibrations were performed using an electromagnet, a permanent magnet, and a mass comparator to measure applied force-per-voltage at a fixed distance.





Measured: 0.47g/V weight change per electromagnet voltage
(Separation: 0.76inch electromagnet to magnet)





Measured: 326μm/V displacement per voltage (control setup)
Measured: 1,060μm/V displacement per voltage (test setup)
(Mass Difference: 1.24kg control mass > test mass)

Pendulum-Displacement-to-Applied-Force Ratios:

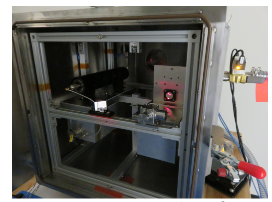
Control: 0.07μm/μN = 326μm/V / (0.47g/V * 9.8m/s^2)
Test: 0.23μm/μN = 1,060μm/V / (0.47g/V * 9.8m/s^2)

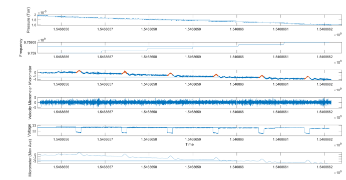
Test Considerations:

Prime Lightworks test results demonstrate torsion pendulum stability below NASA thrust-to-power ratio of 1.2mN/kW (28 μN thrust per 50W RF power.) Future measurements of thrust from RF resonant cavity thrusters will incorporate magnetic shielding, vibration dampening, and resonance optimization, to ensure suitably low-noise environment for thrust measurements.

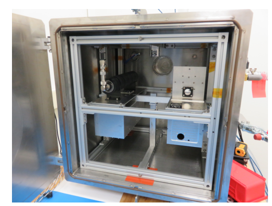
Control Results:

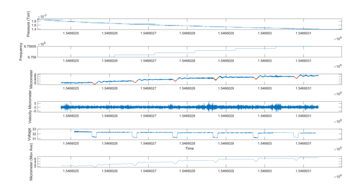
Prime Lightworks has completed control test measurements of 50W RF power electronics and RF attenuator. Control tests were performed in both forward and reverse configurations, by changing the orientation of electronics enclosure and attenuator, as well as in forward configuration with added magnetic shielding (mu-metal) power electronics enclosure.



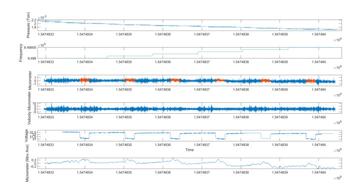


Forward Configuration: +2μm pulse (positive direction)





Reverse Configuration: -2μm pulse (negative direction)



μ-Shielded Configuration: +0.2μm pulse (positive direction)

Thrust Measurements:

Forward Configuration: +28μN = +2μm / (0.07μm/μN)
Reverse Configuration: -28μN = -2μm / (0.07μm/μN)
μ-Shielded Configuration: +3μN = +0.2μm / (0.07μm/μN)

References:

[1] Harold White, Paul March, James Lawrence, Jerry Vera, Andre Sylvester, David Brady, and Paul Bailey. "Measurement of Impulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum", Journal of Propulsion and Power, Vol. 33, No. 4 (2017), pp. 830-841.
[2] Tajmar, M. and Fiedler, G., "Direct Thrust Measurements of an EM Drive and Evaluation of Possible Side-Effects", AIAA Joint Propulsion Conference, AIAA-2015-4083, Orlando, July 27-29 (2015).