Null Result for Prediction of Asymmetrical Anomalous Force from Frustum-shaped RF Resonant Cavity.

Feb, 2016

Eugene Samsonov[1]

9726 216th Ave NE, Redmond, WA 98053.

E-mail: eas0171@gmail.com

This paper describes the experiment conducted by the author to verify predictions of the controversial theory by R. Shawyer where a frustum-shaped RF resonant cavity ("EmDrive") is expected to produce an asymmetrical anomalous force. A resonant cavity has been designed, simulated, and constructed, followed by a dynamic test on a pendulum platform while being energized with approximately 30W of RF power at the TE012 resonance mode. No force resulting from the application of RF energy has been detected within the resolution of the experimental setup. Spurious forces of thermal origin have been observed.

Introduction

The promises and claims of resonant RF cavities producing "thrust" have been known for more than 15 years. A number of controversial theories ([1] [2]) have been published attempting to explain the potential phenomenon, yet there is very little evidence to the fact that the phenomenon described is even real and that it is not just an artifact of various spurious forces resulting from differences in air pressure or Lorentz forces acting on the RF cavity under test. As the forces predicted by R. Shawyer theory [1] appeared to be relatively large (on the order of a few hundred µN from as little as 30W of applied RF power), the author decided to conduct a simple experiment to verify this prediction.

Experimental Setup

The system was built consisting of an acrylic test platform (Figure 1) suspended from the ceiling on 3 meters of thin (0.28 mm) tungsten wire and including the RF cavity being tested, a power RF amplifier, a programmable RF generator with non-volatile memory, a LiPo battery, an XBee wireless control link and some miscellaneous interface and power supply modules. The other part of the test setup included the base platform carrying a laser displacement sensor with resolution of 1 µm, a 16-bit data acquisition and control module, and the other end of the XBee wireless link. The base platform further included one side of electrostatic attraction plates connected to a controlled high voltage (1kV) power supply, while the second electrostatic plate was mounted on the suspended test platform. There were no physical wires

[1] Senior Software Engineer at Microsoft Corp. The author conducted this work in his spare time and using his own funds. This work is not sponsored or endorsed by Microsoft Corp.

of any kind crossing between the base platform and the suspended test platform. The control signal to turn RF power on was transmitted via the XBee wireless link.

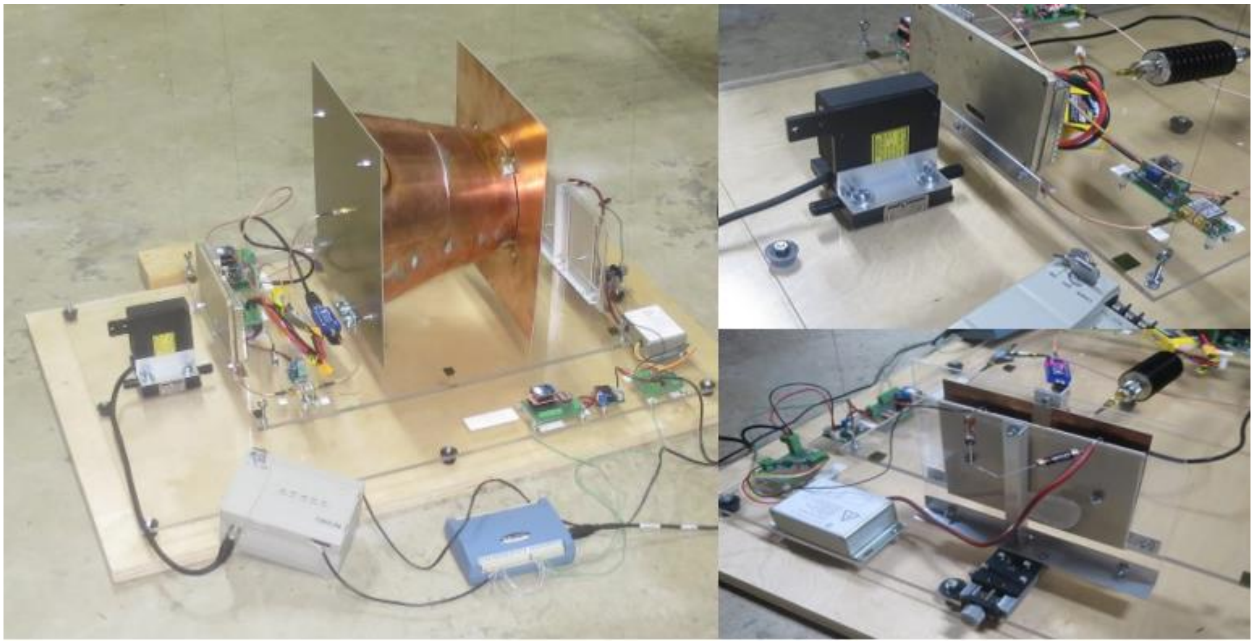


Figure 1. Test platform showing RF cavity, laser distance sensor and electrostatic attraction plates.

A custom control and data acquisition software has been written in C# to facilitate the experiment.

The suspended test platform being a pendulum was allowed to oscillate freely. From geometry and physics of a basic pendulum (Figure 2) it follows that for a small angle ∝ the force acting on pendulum mass along the x axis is given by:

$$F = m * \ g * \frac{\sin(\propto)}{\cos(\propto)} \approx -m * g * \frac{x}{L} \qquad (1)$$

The mid-point of pendulum oscillation corresponds to F = 0 and hence x = 0. Where an auxiliary external force F' is present along the same x axis, then for small F' the new mid-point position x0 will be directly proportional to F' magnitude:

$$F' + F(x0) = 0$$

$$F' = \ -F(x0)$$

$$F' = x0 * \frac{m*g}{L} \qquad (2)$$

Thus by sampling and recoding the pendulum position over time and then calculating and extracting the mid-point values of oscillation it is possible to detect small forces acting on the pendulum in the horizontal direction using the scale factor derived from the pendulum weight and the suspension length as in (2) above.

This method of force detection was employed during the experiment. For the pendulum platform weighing 4 kg and being suspended on 3 m of wire the scale factor comes to 13 µN / µm.

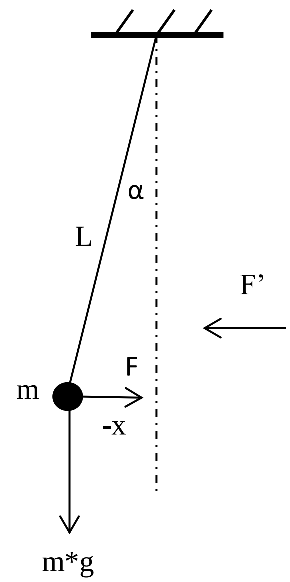
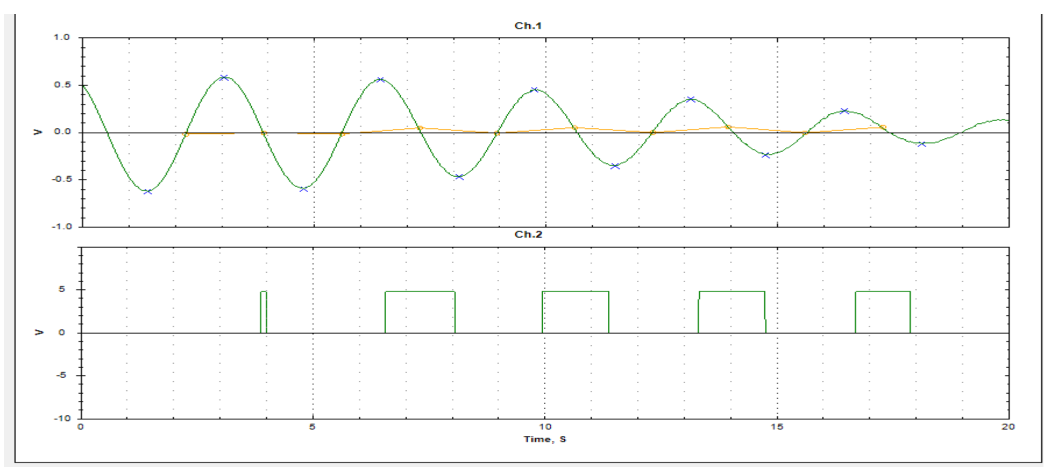


Figure 2. Pendulum geometry.

The experimental setup also included a pair of electrostatic attraction plates made from copper clad FR4 material and used to apply a small controlled force to the test platform to verify the veracity of design. The same electrostatic plates were also used as a computer-assisted damping solution for the pendulum platform, where a high voltage pulse was repeatedly applied at precisely calculated moments derived from sampled pendulum position in order to reduce the amplitude of natural oscillations (Figure 3).



Ch1. Pendulum position (1V = 1000 um) and mid-points of oscillation over time.
Ch2. Control signal to enable high voltage to electrostatic plates.

Figure 3. Electrostatic plates used for damping pendulum oscillations.

RF Cavity Design

A frustum-shaped copper resonance cavity was designed to have its TE012 resonance mode in the center of the RF power amplifier frequency band – around 2,323 MHz. A novel 2-loop coaxial coupler [3] (Figure 4(d)) was used to excite the TE mode. The cavity was simulated in COMSOL© confirming the expected resonance frequency and coaxial coupler performance (Figure 4 (a)). Simulated unloaded Q factor for the cavity was around 75,000. The author then built the actual cavity from a sheet of 0.5 mm copper using a pair of FR4 plates for side walls and verified its resonance modes with a scalar network analyzer (Figure 4(c)).

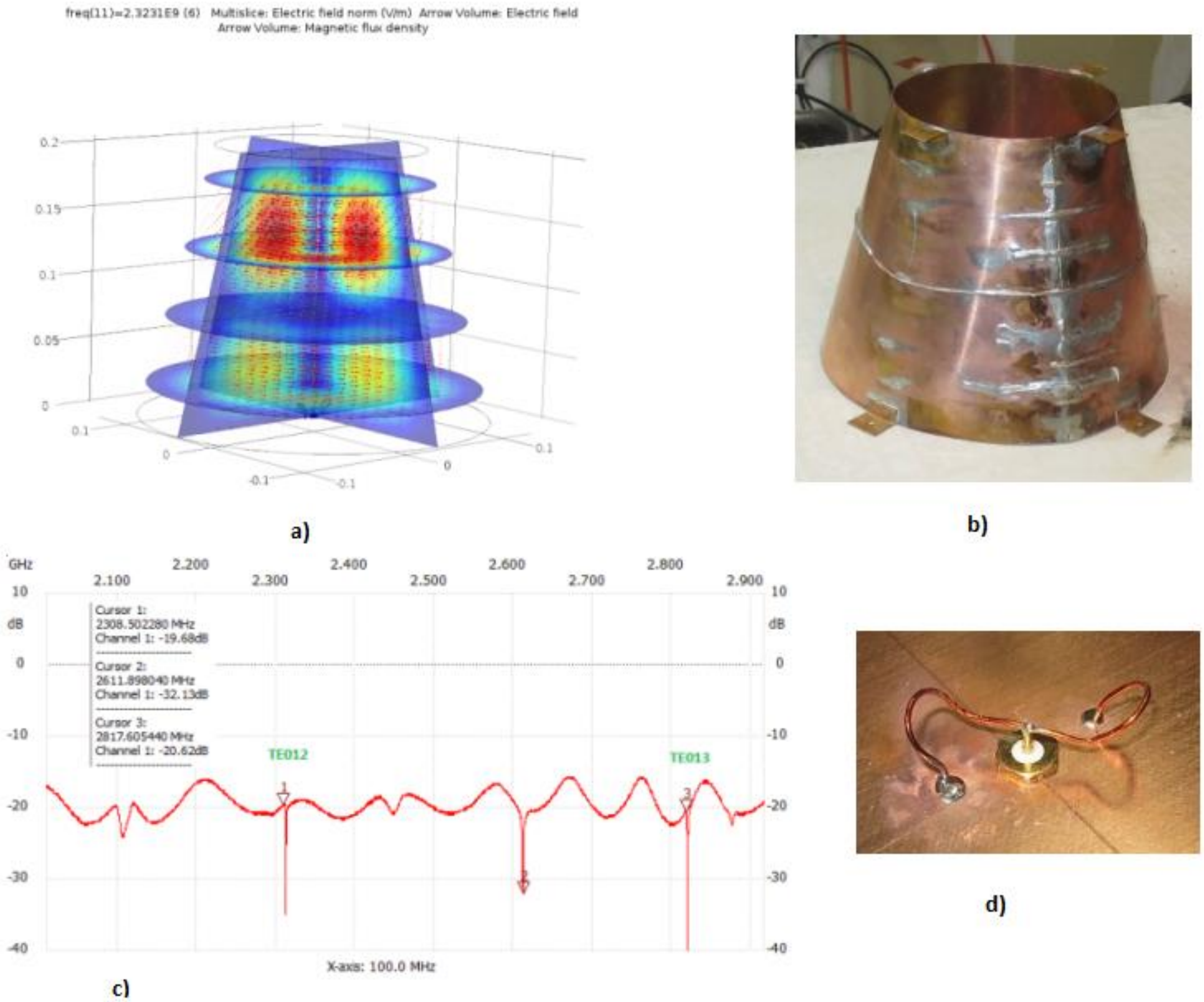


Figure 4. RF cavity. (a) COMSOL(c) simulation of TE012 resonance mode. (b) Copper frustum as-built. (c) S_{11} frequency scan using a -20 dB directional coupler. (d) Coax coupler on the big end plate.

The as-built frustum turned out rather crude (Figure 4 (b)) which was immediately reflected in its measured (loaded) Q factor being only about 3,100. However, its resonance frequency was still very close to the predicted value (2,308 MHz actual vs. 2,323 MHz simulated). No further attempt has been made to improve the Q value with an assumption that the theory being tested does not impose any minimum threshold for the Q value and that also, if any anomalous force were to be observed, one could then proceed to increase the Q value and check if this would have any effect on the anomalous force. The original frustum has been built to the following dimensions:

Big end Diameter, mm	Small end Diameter, mm	Center Length, mm	Predicted TE012 frequency, MHz	Actual TE012 frequency, MHz	Actual Q factor (loaded, measured at -3 dB of S_{11})	Predicted "thrust" at 30W RF power (for as-built cavity), µN
264	158	204	2,323	2,308	3100	950 / 0[2]

After testing this frustum on the pendulum platform (as described below) and observing no anomalous force the author received feedback suggesting that the actual frequency for the TE012 mode of this cavity (2,308 MHz) was below the "cut-off" frequency (2,313 MHz, for calculations see [4]) for the frustum small end as specified in the theory being tested, and hence no "thrust" was expected to be produced. The author then proceeded to modify the original cavity by cutting 8 mm from the frustum small end, resulting in these new dimensions:

Big end Diameter, mm	Small end Diameter, mm	Center Length, mm	Predicted TE012 frequency, MHz	Actual TE012 frequency, MHz	Actual Q factor (loaded, measured at -3 dB of S_{11})	Predicted "thrust" at 30W RF power (for as-built cavity), µN
264	162	196	2,343	2,331	2300	640

The modified cavity now had its TE012 mode frequency (2,331 MHz) 75 MHz above the "cut-off" frequency (2,256 MHz) for the frustum small end thus no longer violating the corresponding theoretical requirement, yet the subsequent testing on the pendulum platform still showed no anomalous forces being produced from the applied RF pulse.

Test protocol

The following general procedure was used for dynamic testing on the pendulum platform:

1. A test article – either the frustum-shaped RF resonant cavity or a 50W 50 Ohm dummy RF load placed on the platform and connected to the RF power amplifier via a -20 dB directional coupler.
2. The platform powered up by a LiPo battery, RF power turned on, and a bench-top RF power meter used to measure the reflected power from the test article.

---

[2] The predicted value of zero comes when considering that this frustum as-built violates the small end "cut-off" frequency condition.

a. At this step the RF generator frequency was adjusted as necessary to hit the minimum of S_{11}. The frequency value has then been programmed into the RF generator non-volatile memory.

3. RF power turned off, the RF power meter disconnected and the test platform stabilized by hand to reduce oscillation amplitude to under 1mm. At this point there were no physical wires connected to the pendulum platform.
4. Computer-controlled electrostatic damping initiated to reduce oscillation amplitude to under 100 µm.
5. A test run performed lasting between 60 to 80 seconds, starting with a period of idle oscillations, followed by applying either an RF pulse or a test high voltage electrostatic pulse or a combination of the two, followed by another idle period (Figure 5(a)). For the entire duration of the run the pendulum platform position has been sampled at a rate of 100 samples per second, recorded and then post-processed to detect mid-points of each oscillation cycle. Changes to mid-point positions were analyzed to check for any forces acting on the pendulum platform (Figure 5(b)).

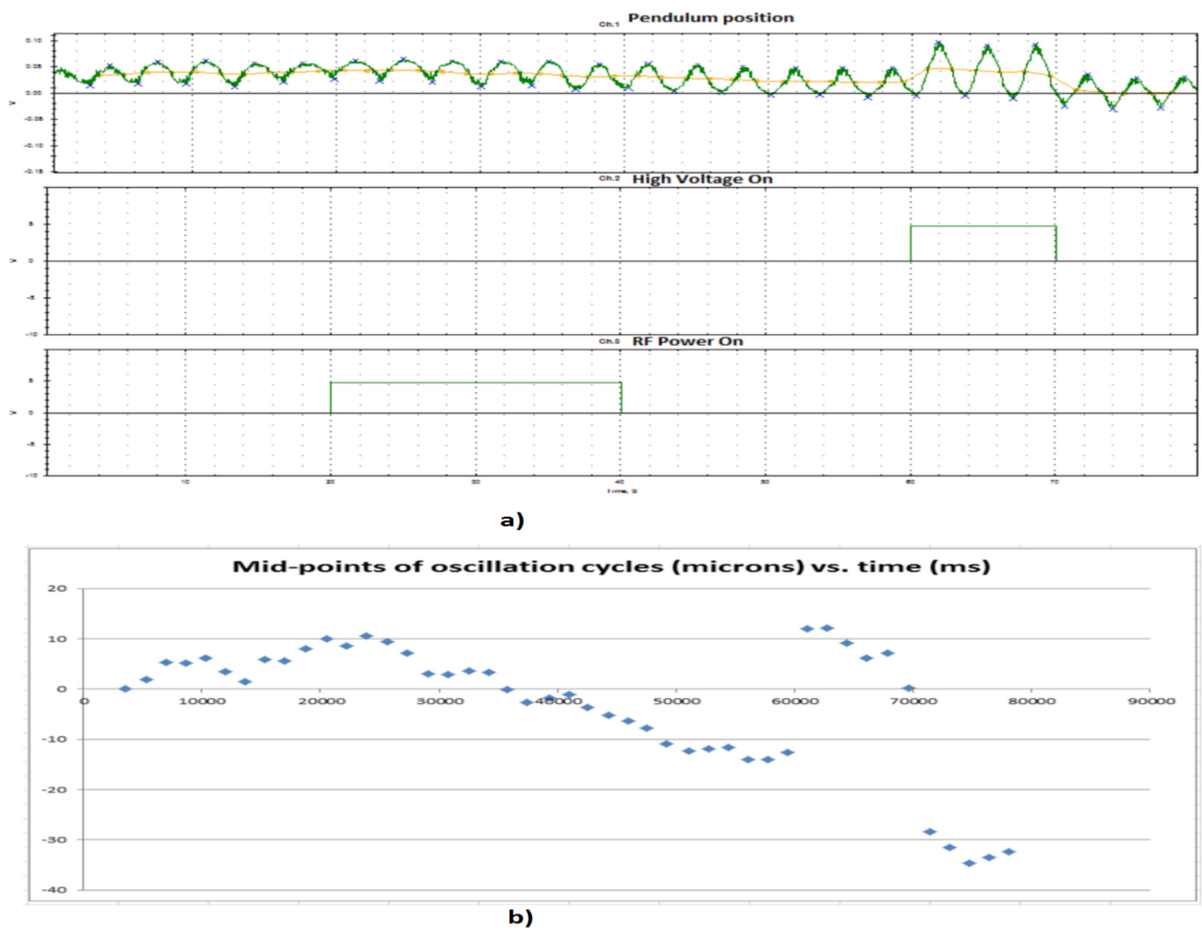


Figure 5. Test run on a pendulum platform. (a) Pendulum platform position and control signals. (b) Change to mid-point positions of each oscillation cycle vs. time.

Reflected RF power was measured with a bench-top RF power meter both before and after each series of test runs. The control signal to turn RF amplifier on during the actual test run was verified visually by observing the control LED as well as by monitoring the battery voltage with a small digital voltage meter located on the pendulum platform. The power RF amplifier consuming 10A when enabled, the battery voltage drop was clearly visible. The RF power delivered to the frustum cavity (the difference between the applied and reflected power) was no less than 27.5 W (typically between 29.0 to 29.7W for the majority of test runs).

More than 50 test runs have been conducted according to this procedure.

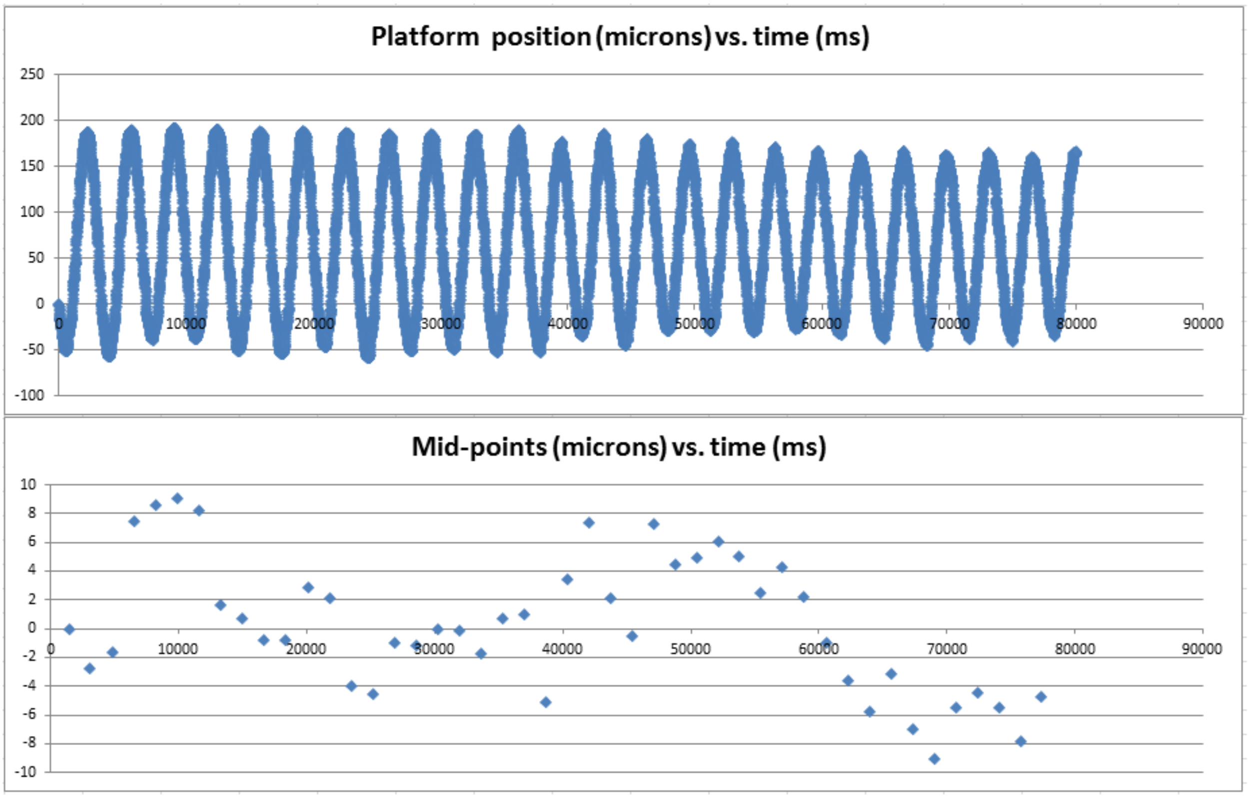


Figure 6. Idle run (no RF pulse and no High-voltage pulse).

Results summary

In all tests involving the frustum-shaped RF cavity, no changes were observed to the mid-points of the test platform oscillations which would be co-incident with the applied RF power. At the same time in all the runs where a high voltage test pulse was employed, the corresponding electrostatic attraction force was easily observable via changes to mid-point positions. The electrostatic force of as low as 160 µN was easily detected and was co-incident with the applied high voltage pulse. Hence it is reasonable to conclude that the predicted anomalous force expected to be on the order of 600+ µN was not present.

All test runs exhibited varying levels of noise and spurious forces, typically being under 200 µN (Figure 6). A few runs being particularly quiet allowed to place an upper boundary on the magnitude of any anomalous force which might be present but below the resolution of the setup. Figure 7 shows one such test run suggesting that any anomalous force, if present, must be under ~40 µN which is more than an order of magnitude below the predicted value.

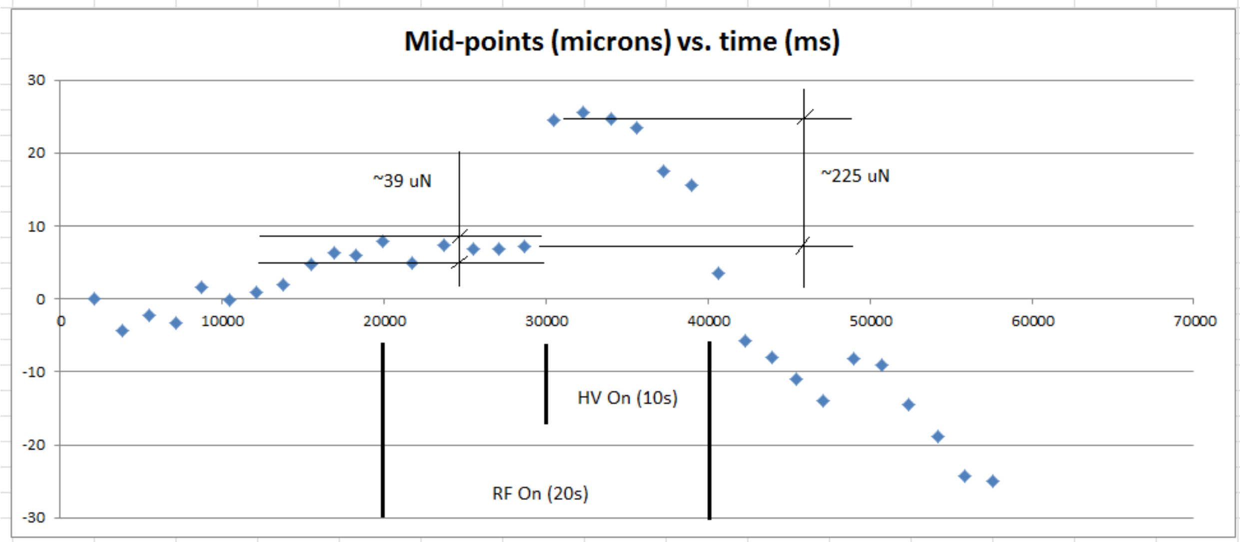


Figure 7. Low noise test run with electrostatic test pulse overlapping the RF pulse.

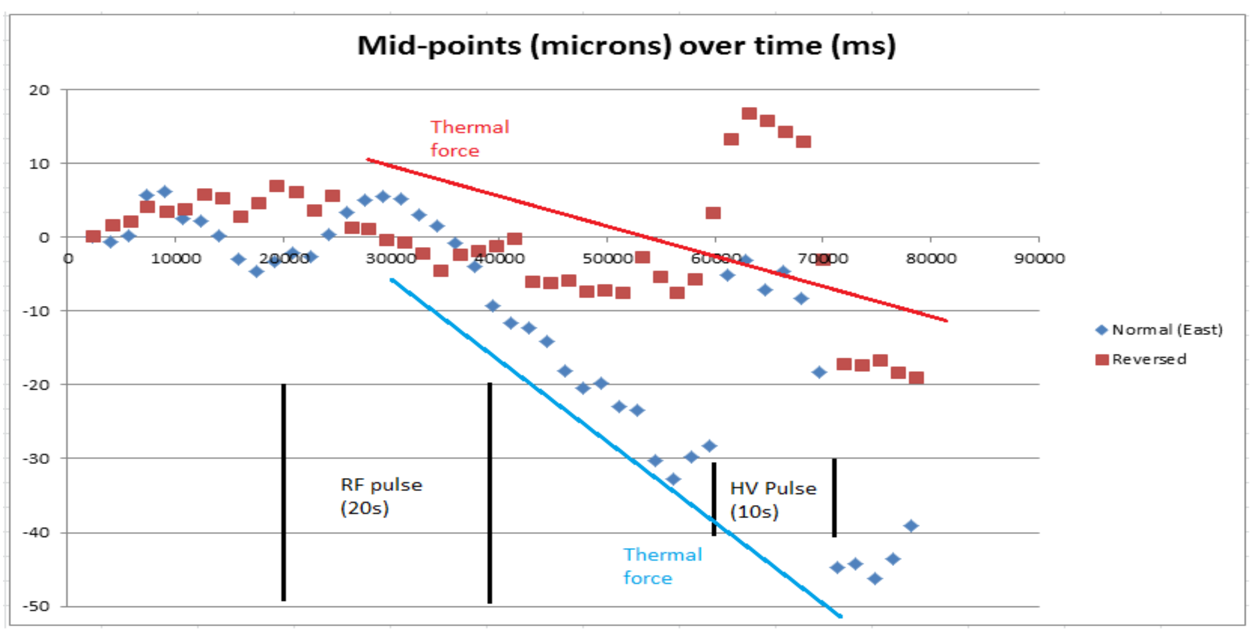


Figure 8. Spurious thermal forces depend on frustum orientation.

Spurious forces observed

The pendulum platform has been found to be sensitive to slightest air movements, including noise from a nearby fridge and a heating furnace, both of which had to be turned off for the duration of the test. Still, the setup remained sensitive to other noise sources, such as sound of heavy rain outside and structure vibrations. However, none of these forces were correlated with the applied stimulus (either the RF or the high voltage test pulse). Yet there was another spurious force observed which the author believes to be of thermal origin and is attributing it to the fact that the aluminum heat spreader plate of the RF power amplifier was getting moderately hot (60-80 °C) during test runs and resulting in one or both of the following effects:

1. "Chimney" effect. The hot air around the heat spreader plate raising up and creating air movement (and changes to air pressure) around various components located on the test platform, the frustum RF cavity being one of those. Any changes to component orientation will now result in changes to this thermal force which was the observed case (Figure 8). This force is present long after the RF power has been turned off and it is also present in test runs with a dummy RF load.

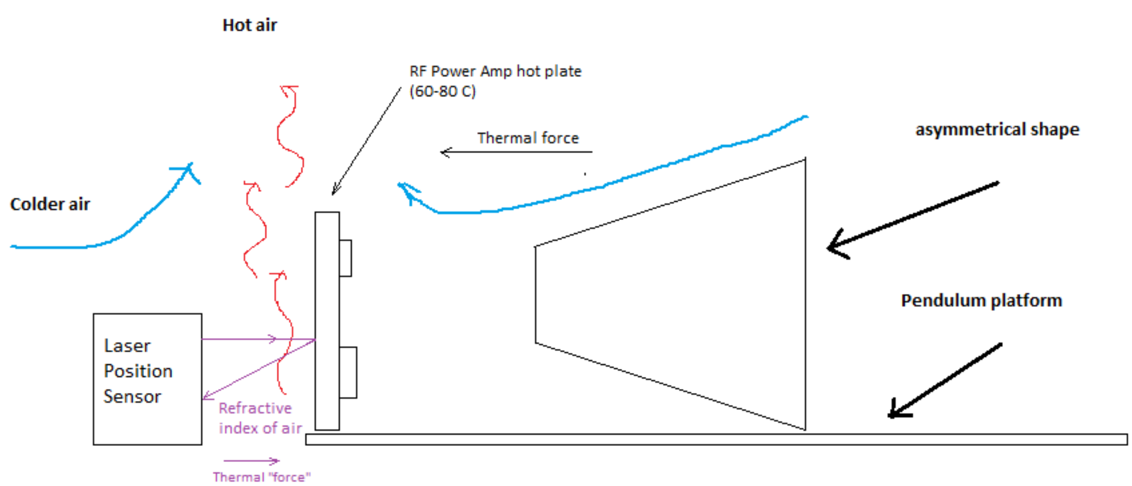


Figure 9. Potential sources of spurious thermal forces.

2. Changes in refractive index of air with temperature. One side of the aluminum heat spreader plate was used as a target for the laser displacement sensor (Keyence LK-2001), the latter using triangulation for its operation. Hence a change in air refractive index is likely to result in changes to the detected position which will then be interpreted as a "force" acting on the pendulum platform. The sensor specification provides a single temperature fluctuation parameter of 0.01% of full scale/°C without further explaining how much of it is due to electronics thermal drift vs. changes to refractive index. The worst case is then rather unpromising, suggesting a change of up to 30 µm per 60°C (the full scale range for this sensor being 5 mm), while the author's own estimate for the contribution from changes in air refractive index is only about 2 µm per 60°C (taking a change in air refractive index of $5*10^{-5}$ per 60°C and the sensor working distance of 30 mm). This gives a range of between 2 µm to 30 µm which, using a scale factor of 13 µN / µm for

the pendulum platform, translates to a potential spurious thermal force of between 26 to 390 µN.

The thermal force was observed starting somewhere in the middle of the RF pulse, often changing direction after a few seconds and then continuing for many seconds after the end of the pulse. However, there is hardly anything anomalous about the origin of this force.

Conclusion

Frustum-shaped RF resonant cavity has been designed, constructed, and tested on a dynamic pendulum platform using 30W of applied RF power at its TE012 resonance mode. The pendulum platform setup has been shown to be able to reliably detect forces as small as 160 µN. The predicted magnitude of an anomalous force for the test cavity (per [1]) was 600+ µN, yet no anomalous force was observed. The corresponding theoretical approach has thus been wholly or partially falsified.

The experimental setup was found to be very sensitive to various spurious forces caused by air movement and dominated by those resulting from hot air convection.

Appendix

Bill of Materials (partial)

Item	**Description**
Data Acquisition module	Measurement Computing USB-1608G
Laser displacement sensor	Keyence LK-2001
High Voltage power supply	ATHV12V6KV1MAW from analogti.com
XBee control link	XBee 1 mw 802.15.4 modules
RF signal generator	SynthUSBII from windfreaktech.com
RF Pre Amp, 10 mW	Mini Circuits ZX60-6013E-S+
RF Power Amp, 30W	Spectrian Class A Linear RF amplifier 2.3-2.45 GHz 2304 ATV+

Nomenclature

F = combined force acting on the pendulum platform in horizontal direction, N
F' = an auxiliary force acting on the pendulum platform in horizontal direction, N
g = standard gravity = 9.80665 m / s2
L = Length of the pendulum suspension, m
m = pendulum mass, kg
S_{11} = Scattering parameter, power reflection coefficient, dB
x = horizontal offset of pendulum platform from equilibrium position, m
x0 = horizontal position of the pendulum platform at equilibrium, m
∝ = angle position of pendulum platform, radian

Acknowledgments

The author would like to thank the participants of the "EMDrive Developments" forum at www.nasaspaceflight.com for their constructive and timely feedback while conducting this experiment.

References

[1] R. Shawyer, "Microwave Propulsion - Progress in the EMDrive Programme," *Proceedings of the IAC Conference, IAC-08.D1.1.01,* 2008.

[2] M. E. McCulloch, "Can the Emdrive Be Explained by Quantised Inertia?," *Progress In Physics,* vol. 11, no. 1, 2015.

[3] B.-Q. Z. L. A. a. Z. Z. H. Zhang, "A novel dual-loop coupler for one-port cylindrical cavity permittivity measurement.," *Progress In Electromagnetics Research,* vol. 127, pp. 537-552, 2012.

[4] D. M. Pozar, in *Microwave Engineering, 4th Edition*, JohnWiley & Sons, Inc., 2012, pp. 127-128.