Direct Thrust Measurements of an EM Drive and Evaluation of Possible Side-Effects

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The EMDrive has been proposed as a revolutionary propellantless thruster using a resonating microwave cavity. It is claimed to work on the difference in radiation pressure due to the geometry of its tapered resonance cavity. We attempted to replicate an EM Drive and tested it on both a knife-edge balance as well as on a torsion balance inside a vacuum chamber similar to previous setups in order to investigate possible side-effects by proper thermal and electromagnetic shielding. After developing a numerical model to properly design our cavity for high efficiencies in close cooperation with the EM Drive's inventor, we built a breadboard out of copper with the possibility to tune the resonance frequency in order to match the resonance frequency of the magnetron which was attached on the side of the cavity. After measuring the Q-factor of our assembly, we connected the EMDrive to a commercial 700 W microwave magnetron. Our measurements reveal thrusts as expected from previous claims (due to a low Q factor of <50, we observed thrusts of +/-20 µN) however also in directions that should produce no thrust. We therefore achieved a null measurement within our resolution which is on the order of the claimed thrusts. The purpose of the test program was to investigate the EMDrive claims using improved apparatus and methods. To this end it was successful in that we identified experimental areas needing additional attention before any firm conclusions concerning the EMDrive claims could be made. Our test campaign therefore can not confirm or refute the claims of the EMDrive but intends to independently assess possible side-effects in the measurement methods used so far. We identified the magnetic interaction of the power feeding lines going to and from the liquid metal contacts as the most important possible side-effect that is not fully characterized yet and which needs to be evaluated in the future in order to improve the resolution.

Nomenclature

c	=	speed of light = 3×10^8 m/s
f	=	frequency
F	=	force
P	=	power

I. Introduction

All present propulsion systems rely on the exchange of momentum and therefore require either propellant on board (chemical, nuclear electric propulsion) or an external field/radiation pressure against which they can push (electromagnetic tethers, solar sails)[1]. Only the concept of the photon rocket may be seen as a true propellantless propulsion system as it converts onboard electric power into directed radiation that in turn produces thrust. However, the thrust is exceptionally small ($F=P/c$) where megawatts of power are needed to generate milli-Newtons of force. Therefore, such a propulsion system has only been studied as a concept so far. Recently, Bae[2] demonstrated that this force could be drastically increased by pumping radiation between two highly reflected mirrors. However, here two satellites are required and only a relative radiation force between the two can be generated.

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Some years ago, Shawyer[3-7] claimed to have invented yet another type of propellantless propulsion system called EMDrive that only uses onboard electrical power similar to the photon rocket, but with orders of magnitude more thrust and without the need of another satellite. If true, this could certainly revolutionize space travel. His concept is illustrated in **Fig. 1**. Microwaves (e.g. generated using a Magnetron) are guided through a waveguide into a tapered cavity which is highly reflective on the inside boundaries. He refers to the work of Cullen[8] who says that the group velocity of a microwave depends on the diameter of the waveguide. Shaywer then interprets the tapered cavity as two waveguides with different group velocities and therefore different radiation pressures at the ends. This is claimed to result in a net radiation pressure that scales with the Q factor (amount of reflections inside the cavity before the radiation is absorbed) of the cavity. As Newton's law of action and reaction must be conserved, the whole thruster is then supposed to react against the inside radiation pressure in the opposite direction which can be used to propel e.g. a spacecraft. The thrust direction should therefore point from the larger to the smaller diameter of the cavity.

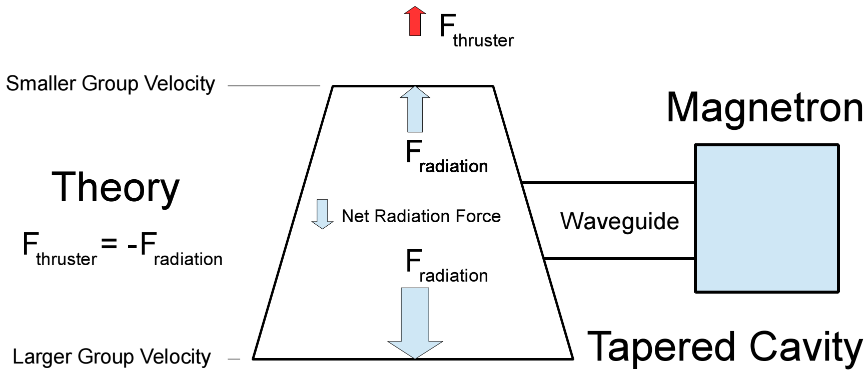


Figure 1. EMDrive Concept.

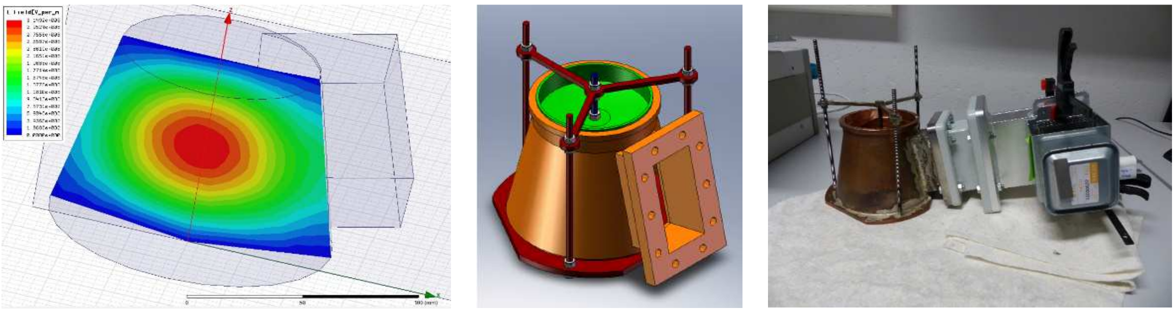
It must be noted that Shawyers analysis and claims are highly controversial (e.g. Ref. 9) as this would obviously violate the conservation of momentum (pushing against itself) following his theory. Aside from the theoretical concept, most interesting are the experimental claims that have been published to date. Shawyer[3] tested the EMDrive on a balance in the upwards and downwards direction observing weight changes (=thrusts) close to his theoretical predictions using precise Q factor measurements with 16 mN using 850 W of microwave power – close to 5600 times larger than expected from pure classical radiation thrust. He claimed to have done checks for thermal and electromagnetic influence. Later testing was done on a torsion balance using air bearings where he observed rotation of the complete apparatus with all electronics and power supplies on-board[6].

Independent tests were carried out in China by Yang et al[10-12] who tested the EMDrive on a force-feedback thrust stand and achieved up to 720 mN of thrust with 1000 W microwave power with even higher Q factors compared to Shawyer. Most recently, Brady et al[13] tested the concept on a torsion balance at NASA with a µN resolution obtaining thrusts of 50 µN using only 20 W of RF power. The microwave electronics were mounted on the balance and power was fed using liquid metal contacts. Strong magnets were used for eddy current damping of the balance and a laser interferometer for monitoring the balance movement. Testing was quite limited (only a few test runs performed, no thruster direction reversal) and interaction with the magnetic damping during operation of the thruster was observed – however below the EMDrive thrust values. A null measurement was performed using a resistor instead of the EMDrive.

So far, all measurements were performed in ambient air, which for sure can lead to significant side-effects like air convection currents or buoyancy due to heat dissipated from the EMDrive. We decided to build our own EMDrive model and to evaluate such side-effects in representative measurement setups similar to the simple balance setup used by Shawyer as well as using a torsion balance similar to the NASA setup. For the first time, we performed some limited tests also in high vacuum completely removing any influence from the ambient pressure.

II. Design and Characterization of EMDrive Thruster Model

We started by designing a model optimized for a frequency of 2.45 GHz using COMSOL in order to be able to use commercial magnetrons used in standard microwave ovens. We iterated our design several times by consulting with R. Shawyer to be as representative as possible. Our final tapered cavity design had an internal top radius of 38.5 mm, a bottom radius of 54.1 mm and a height of 68.6 mm as well as a side entrance for the microwaves as shown in **Fig. 2**. The cavity was made out of three copper pieces with a wall thickness of 3 mm where the lower and middle part as well as the side flange were hard soldered using silver and the top part was able to adapt its position in order to optimize for a high Q factor. A standard WR340 waveguide was then used to connect the magnetron to the EMDrive.



a.) COMSOL Simulation b.) CAD Design c.) Prototype with Waveguide, Magnetron

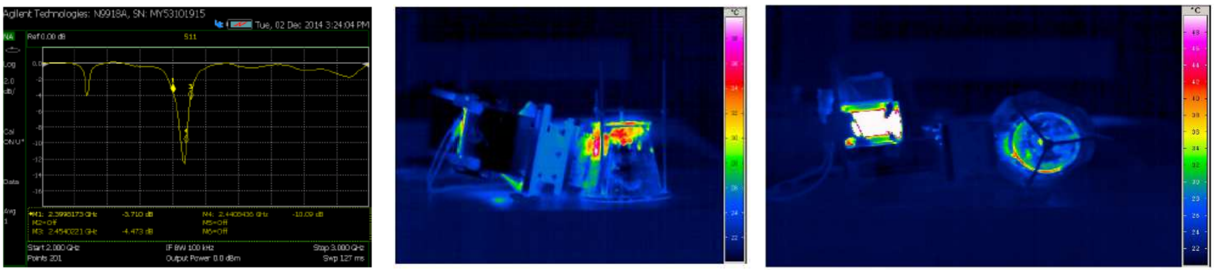
Figure 2. TU Dresden EMDrive Prototype.

The Q factor measurement was then done using a spectrum analyzer (see **Fig. 3a**). Unfortunately, the absorption peak at the resonance we were aiming at was smaller then expected (probably also due to misalignments after soldering). We calculated the Q factor using the difference of the frequencies on both sides of the peak (f_1, f_2) as well as the resonance frequency f_0:

$$Q = \frac{f_0}{f_2 - f_1} = \frac{2.44\ \text{GHz}}{2.45\ \text{GHz} - 2.4\ \text{GHz}} = 48.8 \tag{1}$$

This Q factor is of course much smaller compared to the models from Shawyer, Yang and Brady (which was in the range of 10,000 – 100,000). A much larger resonance peak appeared above 3 GHz, but as we did not have a variable frequency microwave source we had to stick to Q≈50. As our magnetron had an output power of 700 W, we expected a thrust of 98.2 µN according to Shawyer's models. This was much higher than the resolution of our measurement equipment (< 0.1 µN) and we therefore decided to go ahead with testing and explore this low Q factor regime. After all adjustments, epoxy adhesive was used to fix the EMDrive's top part on the cavity. Afterwards, some vibration testing was done and the Q factor measurement repeated to be sure that it does not change after extensive testing.

Next, we used thermal imaging to determine the temperature profile of our EMDrive under power in air. The magnetron itself was by far the hottest part. After a pulse of 90 s, the temperature on the microwave generator easily reached close to 200°C while the smaller diameter part of the EMDrive reached about 35°C (see **Fig. 3b**). If we assume that only the air inside the EMDrive cavity is heated up to an average temperature of 35°C with respect to room temperature, the upward force due to buoyancy is around 70 µN and therefore close to the thrust that we want to measure. Heat and ambient air is therefore indeed a possible error source that needs to be evaluated carefully. However, it should be also easily identifyable as buoyancy thrust only points upwards. We also wrapped thermal isolation (glass wool) around the EMDrive and noted only a temperature increase of 4°C – which was measured more than 4 minutes after power shut down due to the low thermal conductivity through our isolation.



a.) Resonance Measurement b.) Thermal Imaging

Figure 3. Resonance and Thermal Measurement of EMDrive Prototype.

III. Measurements

A. Beam Balance Setup

We first tested our EMDrive on a beam balance setup using a sensitive Sartorius AX224 sxale with a resolution of 0.1 mg which translates into 1 µN. Since the EMDrive was much heavier than the maximum 220 g which the balance can support, the thruster was mounted inside a large aluminum box on one side and counter weights together with the balance on the other side using a knife-egde balance setup[14] on top of a granite table to reduce vibrations as shown in **Fig. 4**. The magnetron was connected with three cables to the high-voltage electronics that was powered by a computer-controlled power supply (two from the HV transformer and one grounding cable). After installation, the box was sealed using an aluminum sheet and tape around the box such that hot air can not easily escape the measurement box. All other surface-edges inside the box where sealed using silicon.

a.) EMDrive inside Measurement Box b.) Measurement Box Sealed c.) Thermal Isolation (Top) and Magnetic Isolation (Bottom)

Figure 4. Balance Test Setup.

In addition to testing the thruster in different directions (upwards, downwards and horizontally – the balance reading was such that an upwards oriented thruster shall give positive weight changes/thrusts), we implemented several different isolation methods (see **Fig. 4c**) in order to evaluate and remove possible effects from electromagnetic or buoyancy influence. Specifically, we implemented:

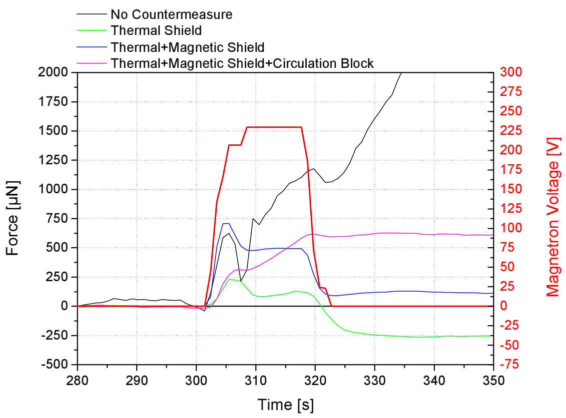
- Thermal isolation: Glass whool wrapped around the thruster and fixed with tape in order to slow down heating of the air around the EMDrive
- Magnetic isolation: Iron sheets with high magnetic permeability were also wrapped around the thruster
- Air Circulation Block: The whole interior of the measurement box was filled up with glass whool in order to reduce any hot air currents inside the measurement box

Moreover, we also checked if the operation of the EMDrive itself does influence the Sartorius balance by powering it up in the same setup but using less counter weight such that the balance was free. The balance reading was stable during turn-on/off and therefore no electromagnetic influence was seen.

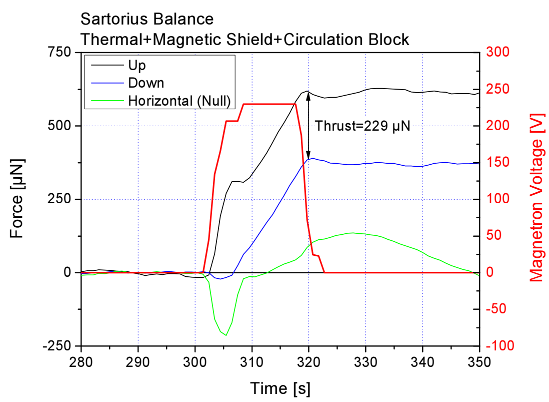
Fig. 5a shows the summary of thruster upwards direction measurements comparing the different isolation methods. The EMDrive was powered up for 15 s with a 600 s delay time before and after the impulse to ensure that any heat generation was sufficiently removed before the next run. The measurements were repeated and signal averaged up to 38 times. We can see in **Fig. 5a** that there is obviously a turn-on effect and then a steady increase after abount 8 s of the measured weight change (thrust). In case of no countermeasure/isolation, the weight change also further increased after turn-off. Thermal shielding significantly reduced the buoyancy effect and the addition of magnetic shielding did not change much of the observed offsets (only the offset at the end of the power peak was different). The implementation of all isolation methods (thermal, magnetic, air circulation block) resulted in the cleanest measurement with an expected behavior such that the thrust appeared after turn-on, then steadily increaseed until power turn off. It then remained there and slowly decreased as the EMDrive cooled down.

Fig. 5b shows then the comparison of upwards, downwards and vertical thruster direction measurements using the full isolation configuration. Remarkably, we can indeed see a fairly large difference between thrust directions. The difference between upwards and downwards measurements was 229 µN and therefore close to our expectation of 2x98 µN. The horizontal direction was supposed to be our zero thrust reference, and indeed it was about only 1/3 of the downwards measurement. Our observations are as follows:

- The balance configuration seems to indeed measure thrust in the correct direction and magnitude as claimed by Shawyer.
- The horizontal direction was supposed to measure only thermal effects and no thrust. We observed a turn-on effect (of the same magnitude compared to other thrust directions but with an opposite value) and then an increase to about 100 µN until the power was turned off. We then saw a behavior that was indeed expected from a thermal side-effect: The thrust still further increased a bit (delay from thermal shielding) and then went down to zero.
- The thruster up/down direction showed a very different behavior. They increased to 620 µN and 391 µN respectively and then remained constant for a much larger time compared to the horizontal direction. A different orientation of the magnetron (horizontal versus vertical) may have caused different thermal signatures and therefore buoyancy effects. Still, this behavior was really different and repeatable. In the much lower power measurements from Brady et al[13] on the torsion balance, we can also see that it took some time after power turn-off that the balance reading went back to zero. This looks like a thermal effect that is still present and was not removed by our isolation efforts.



a.) Summary of Upwards Measurements



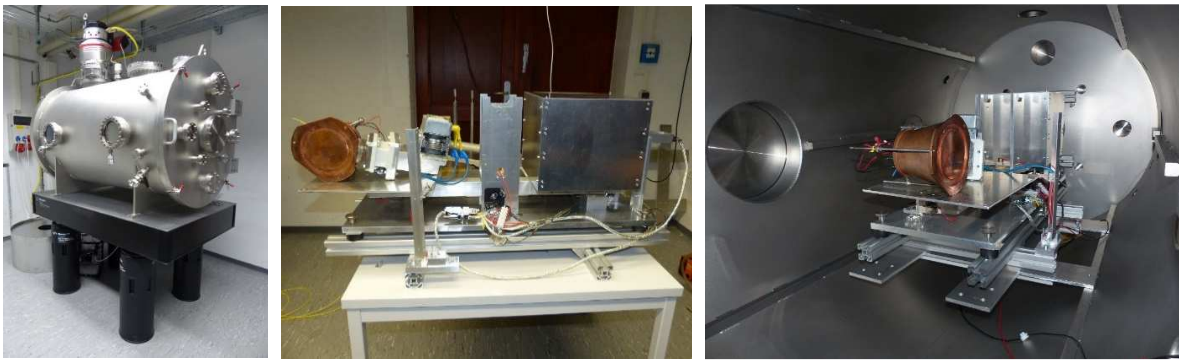
b.) Summary of All Directions with Thermal-, Magnetic-Shielding and Air Circulation Block

Figure 5. Summary of Tests with Balance Setup (Time Axis shows only Part).

Our weakest part in this setup was certainly the simple connection of the magnetron with three flexible silicon isolated wires to the power supply. A current of several Ampere is flowing over those wires which can generate significant magnetic forces (although we tried to keep the wires close together such that the magnetic effects cancel) that may have influenced our measurements. This together with the buoyancy effect made this measurement setup less convincing compared to a torsion balance setup.

B. Torsion Balance Setup in Vacuum Chamber

We have built a torsion balance for electric propulsion testing that can support 12 kg on a balance arm and features liquid metal power feeding (using Galinstan cups), magnetic and fluid damping. We use the attocube FPS laser interferometer with superior resolution and drift characteristics which results in sub nano-Newton thrust resolutions and very low drifts which makes it one of the best thrust balances available today[15]. The torsion balance is mounted inside a large vacuum chamber (1.5 m length and 0.9 m diameter) which sits on top of a Newport optical table to damp it from outside vibrations (see **Fig. 6**). In addition, rubber damping is used inside the vacuum chamber to further isolate the balance. The chamber is equipped with an Edwards XDS35i scroll pump and a Pfeiffer HiPace 2300 turbo pump (>2000 l/s) to achieve a base pressure in the 10^{-7} mbar range. **Fig. 7** shows the different thruster orientations on the balance that we tested: horizontal (positive and negative thrust directions) as well as vertical (pointing upwards). We believed that a vertical thruster orientation would be a better zero-reference compared to the resistor replacement of the thruster as done by Brady et al[13] as here we can better catch the same thermal/magnetic signature. Also, we found out by using a microwave detector that during testing, some microwave radiation was leaking out into the vacuum chamber although the tapered cavity was soldered and glued together. In this setup, the power electronics were outside the chamber (HV transformer, capacitor, diode) and the three connections required by the magnetron (HV plus/minus and ground) were supplied via the liquid metal contacts next to the thruster.



a.) Vacuum Chamber | b.) EMDrive on Torsion Arm | c.) Torsion Balance in Vacuum Chamber

Figure 6. Torsion Balance Setup.

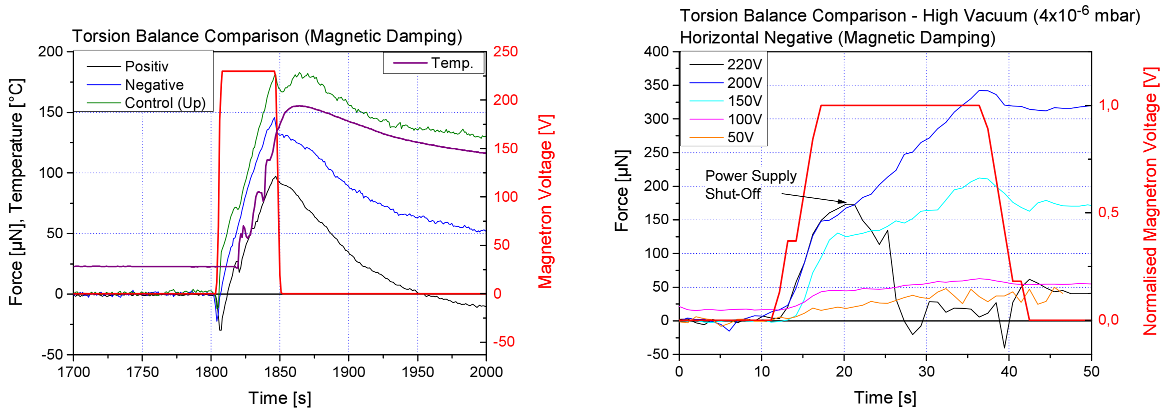
a.) Horizontal Positive Direction | b.) Horizontal Negative Direction | c.) Vertical Direction (Pointing Up)

Figure 7. Torsion Balance Thruster Orientations.

Our testing was first done using magnetic eddy-current damping similar to the setup from Brady et al[13]. We started with tests in ambient air (but closed vacuum chamber) as summarized in **Fig. 8a**. We performed a 40 s impulse with 900 s before and afterwards during each run to allow suffient time for the magnetron to cool down. A temperature sensor (K thermocouple) was mounted on the magnetron and the temperature was logged during the experiments (temperature readout was done on the balance and the digital value transmitted via IR communication without wires to the computer). This ensured that all tests were done with the same thermal signature. Again, all tests (usually up to 10) are signal averaged. Our observations are as follows:

- The control experiment (vertical – upwards direction) actually gave the biggest thrust with up to 224 µN. We could again see a turn-on effect and a steady increase during the power pulse until power turn-off. After that, the thrust values again remained at their high offset and gradually decreased. The slope actually followed quite well the temperature of the magnetron that rose up to around 190°C and then gradually decreased at the same rate confirming our suspicion that this signature has a strong thermal origin.
- The horizontal measurements for positive and negative thruster orientations rose during the pulse up to 96 µN and 145 µN respectively. They showed a similar behavior compared to the vertical direction with a somehow faster decay after power turn-off. The thrust values were now reversed (the positive thrust was smaller compared to the negative thrust). However, considering the fact that the control experiment gave the largest thrust, no conclusion can be derived here. The difference in thrust was 49 µN which led to 24.5 µN for each direction that is about 25% of the thrust prediction according to Shawyer and our measurements with the knife-edge setup before.

We were really puzzled by this large thrust from our control experiment where we expected to measure zero. The power signal to the magnetron consisted of a heater current (up to 5A) which was on high voltage (2000 V) with respect to ground. We disconnected the high voltage power electronics and connected a high voltage power supply running only the same 2000 V through the two cables without any current to check if that created any false signal which it did not. Only when a large current was flowing through the magnetron cables, a large apparent thrust was measured. Therefore, we believed that the anomalous signal must be due to magnetic interaction with our permanent magnet damping.



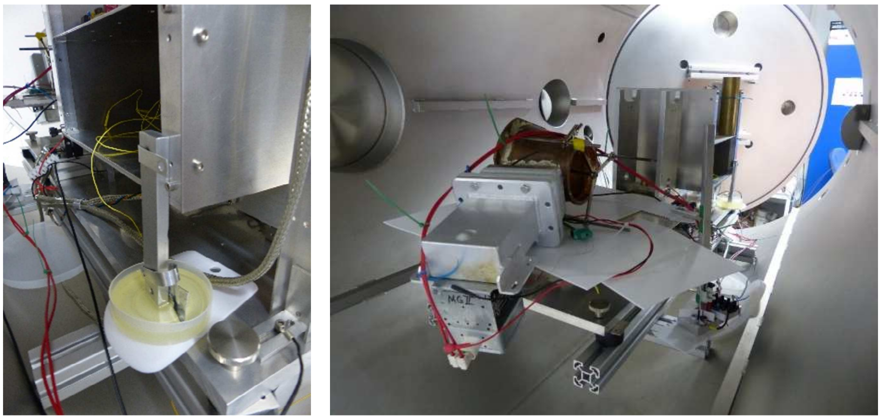
a.) Air Measurements with all Directions

b.) High-Vacuum Measurement of Negative Direction at Different Voltages Supplied to the Magnetron

Figure 8. Summary of Tests on Torsion Balance with Magnetic Damping (Time Axis shows only Part).

However, before changing damping, we tried to assess if air heating/buoyancy effects could still play a role as the signal followed the temperature decay from the magnetron. Therefore, we tested the large horizontal negative thrust direction in high vacuum by evacuating the chamber down to 4×10^{-6} mbar. As shown in **Fig. 8b**, we gradually increased the voltage of our pulse that went into the high voltage power transformer from 50 V up to 220 V (usually we operated at 230 V) – exceptionally, only single measurements were recorded here. According to a magnetron manufacturer, microwaves are starting to be generated if around 150 V are suppled to the HV transformer – however with lower power (unfortunately, we had no equipment to measure the power level at those voltages, but we noted that if we operated below 230 V the temperature on the magnetron did not increase). Indeed we saw that only after reaching 150 V, a thrust appeared on the balance similar in value to the one on air (no thrust for 50 and 100 V). This thrust even increased at 200 V to 325 µN. Interestingly, the thrust now also remained stable and did not immediately return to zero after power turn-off – just as we have seen it with the measurements done on air in **Fig. 8a**. But when we reached 220 V, the power supply shut down due to over current protection around 5 seconds after starting the pulse. Before the power supply failure, the thrust value was very similar to the 200 V case and it decreased to zero shortly after power shutdown (maybe no time to "charge up" the EMDrive). We later found out that there was a thin grey film around our liquid metal cups as if liquid metal had evaporated creating a shortcut. At least we could show that the thrust we measured in vacuum had a similar shape compared to the measurements in air and that they can not be due to any air-related side effect (at least not all of it).

In order to check the magnetic influence hypothesis, we completely removed the permanent magnet from the base of our balance and replaced it with a cup of oil and a fin dipping into the oil and mounted on the balance (see **Fig. 9a**). In addition, we switched the magnetron position such that it now pointed outwards and therefore as far away as possible from our liquid metal connection (see **Fig. 9b**).



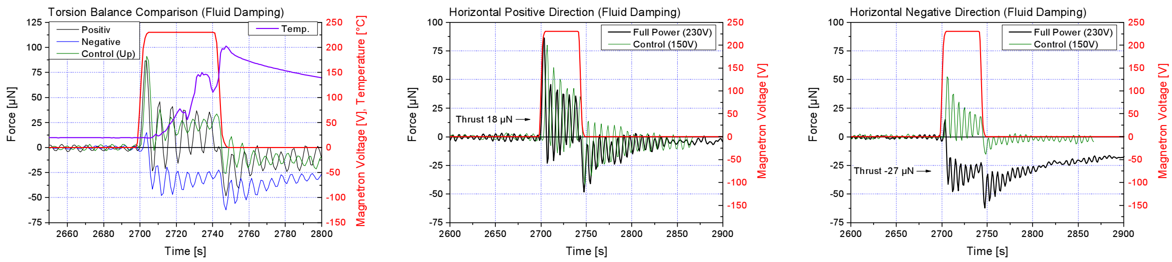
a.) Oil Fluid Damping b.) Magnetron Outer Position

Figure 9. Torsion Balance Setup with Oil Fluid Damping and Magnetron on Outer Position.

Fig. 10 shows our measurements in this setup with oil fluid damping. The damping here is less effective as with the magnetic eddy-currents, however, we can still achieve sub-µN thrust resolutions. In **Fig. 10a**, a summary of all thrust directions is shown. Our observations are as follows:

- We could see the typical balance oscillations and that the thrust values were now greatly reduced.
- Still we noted that the vertical direction (upwards) gave a thrust of around 24 µN which immediately droped to zero when the power was switched off.
- The positive thrust orientation now also went positive up to a value of 18 µN slightly below the vertical direction.
- The negative thrust orientation went indeed negative down to -27 µN. This was the first time that we have actually seen a real thrust reversal. The thrust orientations now coincide again with Shawyer's predictions and our earlier knife-edge measurements. Surprisingly, here also the thrust remained at an offset that slowly degradeed. To a minor extend this was also true for the positive orientation.
- The fact that our control experiment (vertical) showed thrust values similar in magnitude compared to the positive and negative direction actually means that we have performed a null measurement within our measurement resolution (which is on the order of prediction of the EMDrive thrust).

In **Figs. 10b-c**, we show the positive and negative thrust pulses together with control runs powering the magnetron electronics only with 150 V (onset of microwave generation) compared to 230 V. No clear difference can be seen for the positive direction but a clear difference (within the resolution of our measurement) is visible for the negative thrust direction. The magnitude of these thrust measurements are simiar to the ones where magnetic damping was used and are therefore 25% of the original prediction.



a.) Summary of All Directions b.) Horizontal Positive Direction c.) Horizontal Negative Direction

Figure 10. Summary of Tests on Torsion Balance with Oil Fluid Damping (Time Axis shows only Part).

In order to check if the lower thrust may be due to an even lower Q factor at the end of our extensive test campaign, we performed another resonance measurement. Indeed we measured that our Q factor was reduced to only 20.3 – probably due to the fact that our inner surfaces were now much more oxidized compared to the start of our test campaign after a visual inspection. This reduces our theoretical thrust to 41 µN – which is only a third less of what we have measured in our last runs and is therefore well within the expected range.

IV. Conclusion

We have built and tested an EMDrive using a commercial standard magnetron with a resonance frequency of 2.44 GHz and 700 W of power in setups similar to the ones used in the past in order to assess possible side effects and their claimed thrust values. Our thruster had a considerably smaller Q factor (around 50 for the first tests and 20 at the end) compared to others (10,000 – 100,000), however our test facilities had a higher sensitivity as well.

Our first tests were done with a knife-edge balance configuration and we assessed different isolation scenarios in order to see any thermal or electromagnetic influence. As expected, we noticed a large thermal effect that could be significantly reduced by thermal isolation and by blocking any air circulation inside our measurement box. We indeed found thrusts that changed with the orientation of the thruster and magnitudes in line with the theoretical predictions for our low Q factor. After turning off the power, the thrust values in the order of several hundred µN remained and slowly degraded after power shut-off. Considering that the EMDrive and especially the magnetron mounted on it can get hot, such a setup does not seem to be able to adequately measure precise thrusts.

We continued with testing on a torsion balance inside a vacuum chamber. Here we also found thrusts but quickly realized that there was a strong interaction with our magnetic damping system. Still we used this setup to test an EMDrive for the first time in high vacuum down to 4×10^{-6} mbar observing similar thrusts (although at somewhat lower power levels) ruling out any air influence in this configuration. After changing the position of the magnetron (outer position) and replacing the magnetic damping with oil fluid damping, surprisingly we could still observe thrusts that are indeed reversing with thruster orientation but with control runs in vertical direction producing similar thrusts compared to the positive direction. However, negative thrusts were only observed with firing the thruster indeed in a negative direction. Running the magnetron also in this direction at lower voltages produced similar positive values as the vertical control experiment. The thrusts observed with the oil-damped torsion balance were close to the original prediction taking our small Q factor into account (around +/- 20 µN for 700 W of microwave power – still an order of magnitude more effective than pure radiation thrust). We also observed that the thrust appeared not to go down to zero immediately after power is switched-off but rather noted a gradual decrease which still looks like a thermal artefact. The fact that our control experiment (vertical) showed thrust values similar in magnitude compared to the positive and negative direction actually means that we have performed a null measurement within our measurement resolution (which is on the order of prediction of the EMDrive thrust)

The nature of the signals observed is still unclear. Additional tests need to be carried out to study the magnetic interaction of the power feeding lines used for the liquid metal contacts. Indeed many more checks remain like studying effects from outgassing, thermal effects from the magnetron, etc. Our test campaign can not confirm or refute in any way the claims of the EMDrive but intends to independently assess possible side-effects in the measurements methods used so far. We did find a number of side-effects in the previous setups that indeed can produce large false signals. More work is needed to assess other error sources and the source of the signals that we have observed. Next steps include better magnetic shielding, further vacuum tests and improved EMDrive models with higher Q factors and electronics that allow tuning for optimal operation. We believe that this is a good education project to track down measurement errors and as a worst case we may find how to effectively shield thrust balances from magnetic fields.

Acknowledgement

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References

[1]Tajmar, M., "Advanced Space Propulsion Systems", Springer, Wien-New York, 2003

[2]Bae, Y.K., "Photonic Laser Propulsion: Proof-of-Concept Demonstration", Journal of Spacecraft and Rockets, Vol. 45, No. 1 (2008), pp. 153-155.

[3]Shawyer, R., "The Development of a Microwave Engine for Spacecraft Propulsion", Space Chronicles JBIS, Vol. 58 Supplement 1, 2005, pp. 26-31

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

[5]Shawyer, R., "The EMDrive Programme - Implications for the Future of the Aerospace Industry", Proceedings of the CEAS European Air and Space Conference, Manchester, 2009

[6]Shawyer, R., "The EMDrive - A New Satellite Propulsion Technology", Proceedings of the 2nd Conference on Disruptive Technologies in Space Activities, Toulouse, 2010

[7]Shawyer, R., "The Dynamic Operation of a High Q EMDrive Microwave Thruster", Proceedings of the IAC Conference, IAC-13.C4.P.44, 2013

[8]Cullen, A.L., "Absolute Power Measurements at Microwave Frequencies", IEE Proceedings, Vol 99 Part IV, 1952, pp. 100-111

[9]Costello, J.P., "Why Shawyer's 'electromagnetic relativity drive' is a fraud", http://johncostella.webs.com/shawyerfraud.pdf (Accessed 5th July 2015)

[10]Yang, J., Yang, L., Zhu, Y., and Ma, N., "Applying Method of Reference 2 to Effectively Calculating Performance of Microwave Radiation Thruster", J. Northwestern Polytechnical University, Vol 28 No 6, Dec 2010

[11]Yang J.,Wang, Y.Q., and Li P.F., "Net thrust measurement of propellantless microwave thruster, " Acta Phys. Sin, Vol. 61, No. 11, 2012, pp. 110301

[12]Yang, J., Wang, Y.Q., Ma, Y.J., Li, P.F., Yang, L., Wand, Y., and He, G.Q., "Prediction and experimental measurement of the electromagnetic thrust generated by a microwave thruster system", Chin. Phys. B, Vol. 22, No 5, 2013, pp. 050301

[13]Brady, D.A., White, H.G., March, P., Lawrence, J.T., and Davies, F.J., "Anomalous Thrust Production from an RF Test Device Measured on a Low-Thrust Torsion Pendulum", AIAA 2014-4029, 2014

[14]Lőrincz, I., and Tajmar, M., "Identification of Error Sources in High Precision Weight Measurements of Gyroscopes", Measurement, Vol. 73, 2015, pp. 453-461

[15]Bock, D., Rössler, F., Kössling, M., and Tajmar, M., "Development and Testing of Field Emission Thrusters at TU Dresden", Proceedings of the 5th Russian-German Conference on Electric Propulsion, Dresden, September 7-12, 2014