Breakthrough Propulsion Physics: Leave the fuel tank at home

Author: Dan Fries (2018)

While more and more interest exists in utilizing resources outside of our planet's protecting atmosphere, one of the biggest problems remains unsolved: the efficient moving of large masses from Earth and in between stellar bodies. So far, we have relied mostly on Newton's third law in this endeavor, pushing mass out of the back of a rocket at high velocities to generate thrust and impart momentum onto an object in a vacuum. Unfortunately, the laws of physics put stringent limitations on such systems and we end up with spacecraft whose total mass is almost completely made up from stored propellant. For example, flying to the edge of the solar system from a low earth orbit using an ideal liquid hydrogen-liquid oxygen rocket, would require about 85% of the spacecraft mass to be propellant. Thus, making this approach highly impractical for the utilization and colonization of our entire solar system. While there is room for improvement with options such as electrical propulsion, nuclear driven engines, photon rockets, and alternative fuels (including anti-matter), it is very likely that we will never bridge interstellar distances unless we come up with radically new propulsion concepts.

An alternative approach is presented by so-called propellantless propulsion concepts, where the idea is to produce thrust without expelling a reaction mass. An example of such a concept based on well-established physics are some forms of beamed propulsion such as laser and microwave sails. However, beamed propulsion still requires some sort of array emitting the momentum carrying rays pushing the target spacecraft forward. Of course, this means that the propulsive capability decreases rapidly with distance from the array and the spacecraft is dependent on the array to be functioning and within reach. Two other concepts, based on more exotic and less well-understood physical principles, that have been attracting a lot of attention recently are the Mach Effect as well the EMDrive Thruster. Both thrusters are operating on the principle of converting of electricity into a directed force, capable of accelerating an object attached to the thruster.

Such a thruster, if operational, would revolutionize the way we approach space travel. Nonetheless, preliminary results and the underlying working principles should be viewed with a healthy amount of skepticism. For many scientists, such a device violates known laws of physics, most prominently the conservation of energy and momentum. Moreover, independent repetition of the experiments is required to ascertain positive thrust measurements and working principles. In the light of this exciting progress and the need to involve a larger community of researchers, we should take a closer look at the Mach Effect and EMDrive Thrusters.

Mach Effect Thruster

The Mach Effect Thruster (MET) proposed by James Woodward (California State University Fullerton) uses Mach's principle to generate a force in an object that is undergoing mass-energy fluctuations [1]–[3]. The Mach principle states that the distribution of mass and energy in the rest of the universe, and their gravitational interaction with a body, determines the inertia of that body during acceleration. Thus, generating mass or energy fluctuations in a body would allow one to manipulate the inertia of that body. Both experimental evidence and theoretical explanation attempts have been presented for the MET. Woodward's theoretical work attempts to use the non-linear Hoyle-Narlikar theory, which describes gravitation in the framework of electromagnetic radiation reaction theory. A purely linear theory would fail to capture the seemingly instantaneous interaction of particles with the rest of the universe postulated by the Mach principle. The Hoyle-Narlikar theory is fully Machian and reduces to Einstein's theory of gravitation in the limit of matter density distributed as a smooth fluid. It allows for both retarded and advanced waves, the latter of which are a concept used to describe entanglement and instantaneous-like information exchange between particles in the universe (see also emitter and absorber theory in electrodynamics). The advanced waves, in fact, would still be travelling at the speed of light, c, but backwards in time. The result is the so-called "Woodward mass fluctuation formula",

$$\nabla^2\phi = -\nabla\vec{g} = 4\pi G\rho + \left[-\frac{1}{m^2}\left(\frac{\partial m}{\partial t}\right)^2 + \frac{1}{m}\frac{\partial^2 m}{\partial t^2}\right]$$

where ϕ is the gravitational potential, and ρ is the stationary mass density. The first term on the right-hand side corresponds to the contribution to the gravitational field by the properties of a body at rest while the second term in square brackets corresponds to a time varying density or mass. Following the approach by Tajmar [1], integrating over the volume yields for the mass fluctuation term,

$$\Delta m_0 = -\frac{1}{4Gc^2\rho_0}\frac{\partial P}{\partial t}$$

where $\partial P/\partial t$ is a time-varying power input into the body. Tajmar's derivation of this term uses the weak-field approximation to general relativity and Sciana's inertia model, arriving at the same general results as Woodward. The fact that a time varying power input might correspond to the temporal variation of a body's mass also follows from the fact that energy content and mass are directly linked by Einstein's relation $E = mc^2$. Nonetheless, the effect predicted by Mach's principle is orders of magnitude larger than this relation suggests. This variation in mass finally results in a net force acting on the body, if the driving power is configured correctly.

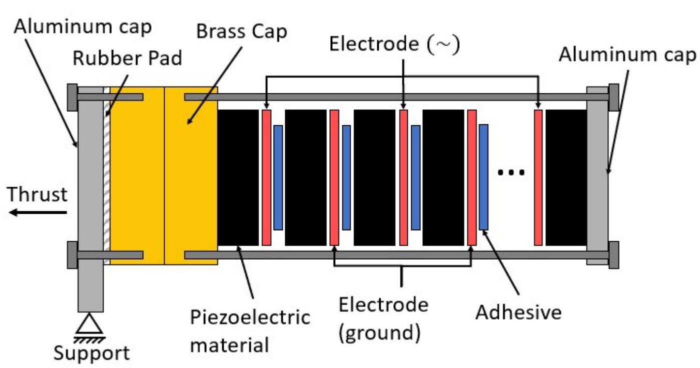

Figure 1: Schematic of an MET prototype, based on the sketch in [1].

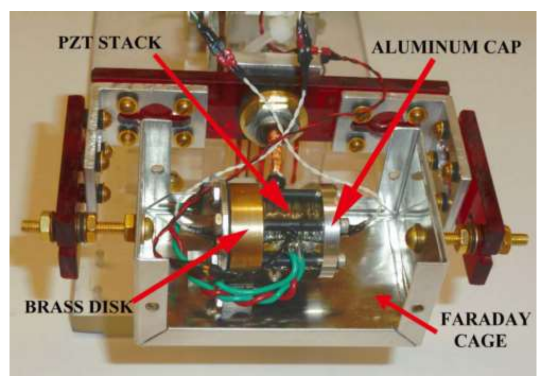

Figure 2: Photograph of a MET test article by Woodward's group [2].

In recent experiments, the time varying power input is realized using stacks of Piezo disks (PZT), as illustrated in in Figure 1 and Figure 2. Applying a voltage to this stack results in an expansion of the stack, which can be translated into an acceleration and to first order $\partial P/\partial t = \partial(Fv)/\partial t \approx m_0 a^2$, where a is the acceleration of the Piezo stack. The experimental results to date show thrust signals on the order of $2\mu N$ for input powers around 200-300 W ($\sim$400 Vpp) and a driving frequency of $\sim 39\ kHz$ [2].

EMDrive

A radio frequency (RF) resonant cavity thruster, also called EmDrive, has been proposed as another concept of reaction mass-less propulsion. The concept was originally proposed by Roger Shawyer [4] and got more attention recently when Harold "Sonny" White (NASA Johnson Space Center) announced that his team had successfully completed the most sophisticated measurements to date, reporting net thrust produced by a working prototype [5]. The basic principle of the thruster has a magnetron feeding microwave energy into a tapered waveguide, as shown in Figure 3. The overall length of the waveguide, or cavity, is such that resonance occurs at the magnetron operating frequency. It is not clear which physical mechanism in this setup would result in a net thrust, but several explanations have been proposed.

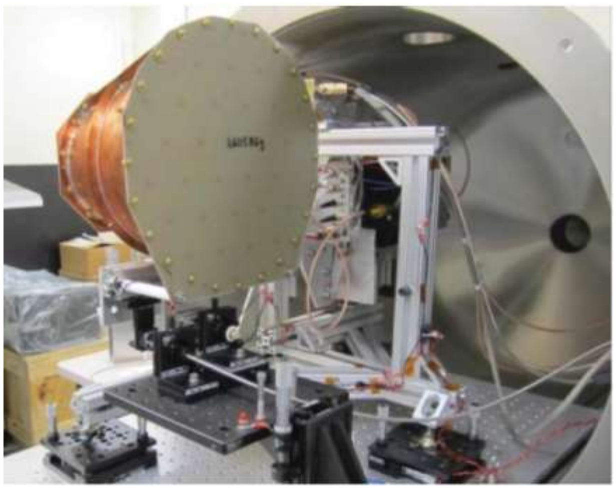

Figure 3: Prototype resonant cavity thruster built by NASA's Advanced Propulsion Physics Laboratory [5]

Shawyer's explanation of the working principle of the EMDrive is that the group velocity of the electromagnetic waves at the larger end section is higher than the group velocity at the smaller end section, resulting in a differential in radiation pressure and a net force. However, this was criticized as violating the laws of electromagnetism and conservation laws. Harold White has suggested the EMDrive could be an example of a quantum vacuum thruster. Such a thruster, also referred to as Q-thruster, would provide a reaction propulsive force extracting work from virtual particles originating in quantum vacuum fluctuations of the zero-point energy field (the latter being analogous to a pilot-wave). Arguments against this kind of explanation are again violations of conservation laws and the questionable existence of a "quantum vacuum virtual plasma" providing the reaction mass necessary for a net force. Other proposed explanations include the "Modified Inertia Hubble-scale Casimir effect", photon leakage, the Mach effect, and the warping of space-time.

In their experimental work, White et al. [5] report that "a dielectrically loaded, tapered RF test article excited in the transverse magnetic 212 (TM212) mode (…) at 1937 MHz is capable of consistently generating force at a thrust-to-power level of 1.2 ± 0.1 mN⁄kW with the force directed to the narrow end under vacuum conditions". They used a copper frustum loaded with a disk of polyethylene as dielectric medium on the smaller end and measured a maximum forward thrust of $119 \pm 6\ \mu N$ at an input power of 80 W using the setup in Figure 4. The corresponding maximum reverse thrust was $74 \pm 6\ \mu N$, while the null-tests showed only the thermal signal and no impulsive element.

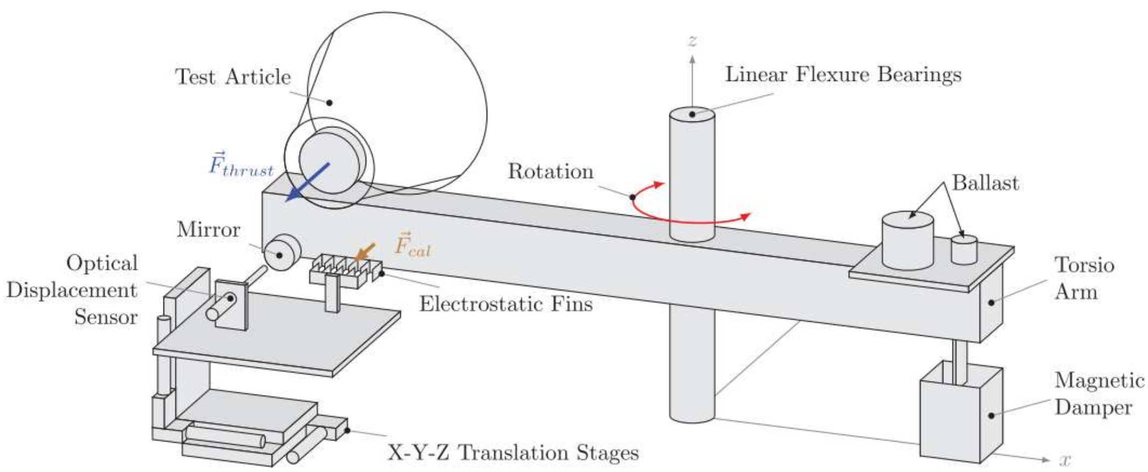

Figure 4: Simplified representation of the torsion pendulum setup used by White et al. [5].

Testing the limits

Although some of the results surrounding the presented propellantless drives seem ground-breaking, measuring thrust in the µN range is extremely difficult and the methods are by no means free from controversy.

One major factor is that experiments measuring such small forces are extremely sensitive and it is difficult to account for all possible sources of error. Factors possibly influencing measurements include, but are not limited to, the vacuum conditions, the occurrence of harmonic oscillations, electromagnetic interference, calibration method and reliability, external vibrations (traffic, seismic activity, oceans), thermal expansion, and outgassing. Thus, the dissemination of results and the report of experimental details is extremely important, to judge whether claims of new physical mechanisms to generate force are believable, or whether additional measurements and precautions are required. Moreover, independent testing of hypothesis and repetition of results is required to confirm hypothesis and measurements.

Very recently, the research group around Martin Tajmar at the Technical University of Dresden has published first results from their “SpaceDrive Project”. The project’s goal is to contribute to the development of breakthrough space propulsion systems. As a first development milestone, the research group is attempting to reproduce findings and further eliminate possible sources of error relating to both the EMDrive and the MET [6]. To get an idea of the effort going into the testing of the working principle of these thrusters one only has to look at the TU Dresden’s testing equipment. They use a torsion balance with sub micro-Newton resolution that has been continuously improved over four years of research. The displacement measurements are achieved optically, and the entire setup is placed into a vacuum chamber which is vibration isolated from its environment. The balance arm and thruster-electronics in the vacuum chamber are electromagnetically shielded, the position of the test article can be fine adjusted using stepper motors, and two different calibration techniques for the torsion balance are used. Finally, the experiment’s temperature is continuously monitored, liquid metal contacts are used to supply the entire setup with power and data signals, harmonic oscillations are damped, and data acquisition is automated as much as possible. In addition, sophisticated test procedures are employed to ensure steady-state measurements and compensate for effects which could cause spurious thrust measurements.

To assess results reported for the EMDrive, the group at TU Dresden built a microwave cavity with the same inner dimensions as White et al. [5] and theoretically similar thrust characteristics. Interestingly they found that the thrust they measured (about double of what was measured by White et al.) was not produced by the microwave cavity but more likely by an interaction between the earth's magnetic field and the current flowing to the device's amplifier. Apparently, no experimental test to date has taken this interaction into account and shielding of the microwave cavity and amplifier is not reported anywhere. This finding necessitates reassessment of existing data, further modifications of the test setup, and additional measurements, as at these experimental scales the interaction is capable of completely masking any potential thrust produced by the EMDrive.

Testing an MET, the team behind the SpaceDrive Project used a thruster directly supplied by Woodward and Fearn (whose work was mentioned earlier in the article). During this series of measurements, the thruster was actually mounted inside an electromagnetically shielded box and shows the characteristics one would actually expect for a functioning propulsive device. That is, a thrust force of 0.6 µN (at 150 W of input power or 150 Vpp) which reverses its direction when the thruster is turned 180° and disappears when turned 90°, i.e. parallel to the torsion balance arm. Nonetheless, further testing of their equipment revealed some anomalous thrust measurements, indicating that some electromagnetic interaction or thermally induced expansion is still masking real thrust values which are expected to be much smaller.

Thus, while the results are not final, they provide extremely important additional data points and pave the way to conclusive results and explanations.

Where does this leave us?

It is clear from the above that the laws of physics are not always straightforward in their interpretation, leaving room for the possibility to find previously unknown propulsion concepts that go beyond classical combustion-based rocket engines. The devices reviewed at this stage provide thrust to input power ratio of $\sim 0.02 - 1.2$ mN/kW, as compared to ~ 50 mN/kW in the case of an ion thruster. Thus, at this point the biggest advantage of the examined propellantless drives would clearly be the enormous mass savings.

However, it has also become apparent that such breakthroughs do not come without a cost. It takes time and larger groups of people willing to derive and re-derive the governing scientific principles, to run and re-run the experiments, and to evaluate and re-evaluate the results. Until it is clear whether a proposed technique works and, more importantly, how it works. Only then can we hope to scale the technology up and to obtain the necessary means to do so. And that, we certainly want to do, if we hope to brave the sea of stars.

Of course, the MET and EmDrive are not the only breakthrough space propulsion concepts being considered, however, reviewing each one of them in more detail would go beyond an article like this. The interested reader could look into Space-Time-Engineering (Warp drive), anti-matter catalyzed fusion propulsion, and photon rockets.

[1] M. Tajmar, "Mach-Effect thruster model," *Acta Astronaut.*, vol. 141, no. September, pp. 8–16, 2017.

[2] H. Fearn, A. Zachar, K. Wanser, and J. Woodward, "Theory of a Mach Effect Thruster I," *J. Mod.*

Phys., vol. 06, no. 11, pp. 1510–1525, 2015.

[3] H. Fearn and J. F. Woodward, “Experimental Null Test of a Mach Effect Thruster,” *J. Sp. Explor.*, vol. 2, no. 2, 2013.

[4] R. Shawyer, “A Theory of Microwave Propulsion for Spacecraft,” 2006.

[5] H. White *et al.*, “Measurement of Impulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum,” *J. Propuls. Power*, vol. 33, no. 4, pp. 830–841, 2017.

[6] M. Tajmar, M. Kößling, M. Weikert, and M. Monette, “The SpaceDrive Project - First Results on EMDrive and Mach-Effect Thrusters,” *Sp. Propuls. Conf.*, no. May, 2018.