Revolutionary Propulsion Research at TU Dresden

M. Tajmar
Institute of Aerospace Engineering,
Technische Universität Dresden,
01062 Dresden, Germany

Since 2012, a dedicated breakthrough propulsion physics group was founded at the Institute of Aerospace Engineering at TU Dresden to investigate revolutionary propulsion. Most of these schemes that have been proposed rely on modifying the inertial mass, which in turn could lead to a new propellantless propulsion method. Here, we summarize our recent efforts targeting four areas which may provide such a mass modification/propellantless propulsion option: Asymmetric charges, Weber electrodynamics, Mach's principle, and asymmetric cavities. The present status is outlined as well as next steps that are necessary to further advance each area.

1. Introduction

Present-day propulsion enables robotic exploration of our solar system and manned missions limited to the Earth-Moon distance. With political will and enough resources, there is no doubt that we can develop propulsion technologies that will enable the manned exploration of our solar system.

Unfortunately, present physical limitations and available natural resources do in fact limit human exploration to just that scale. Interstellar travel, even to the next star system Alpha Centauri, is some 4.3 light-years away which is presently inaccessible – on the scale of a human lifetime. For example, one of the fastest manmade objects ever made is the Voyager 1 spacecraft that is presently traveling at a velocity of 0.006% of the speed of light [1]. It will take some 75,000 years for the spacecraft to reach Alpha Centauri.

Although not physically impossible, all interstellar propulsion options are rather mathematical exercises than concepts that could be put into reality in a straightforward manner. For example, from all feasible propulsion systems ever proposed the highest performance is expected from nuclear bombs which are detonated behind the spacecraft (this concept was originally developed under the name Project Orion) [2]. Even such a system would require an order of magnitude more warheads than presently available just to achieve a fly-by mission to our nearest star within a human lifetime.

Even if we could achieve a good fraction of the speed of light, our practical action radius for human-return missions would still be limited to about 10 light-years which includes a maximum of 10 stars around us where no planets have been detected so far. According to the "Maccone Distribution" [3], the next civilization would be most probably some 2000 light-years away which would be inaccessible even with hypothetical light-speed propulsion systems. It is quite clear that we need some sort of breakthrough in propulsion physics to circumvent these limits and enable practical – and affordable – human exploration well beyond our solar system.

Following the spirit of past programs such as NASA's breakthrough propulsion physics and BAE Systems Project Greenglow, we started our own breakthrough propulsion physics program [4] investigating:

1. Theory: Explore theoretical concepts that can lead to a practical Space/Warp drive, new approach to gravity that can be experimentally tested, etc.

2. Mass Modification: Investigate experimentally if mass is influenced by temperature, rotation, charge/polarization, etc.

3. New Gravitational-Like Fields: Carry out experiments to investigate if gravitational/ frame-dragging fields can be enhanced in the lab e.g. by strong discharges through superconductors

4. Testing other Claims: Critically assess claims by others on revolutionary propulsion concepts of new physical effects that may lead to a breakthrough in propulsion and/or power.

Recent work by our group include a critical evaluation of the EMDrive [5], a replication of the Wallace gravitational generator [6], a superconducting gravitational impulse generator [7], [8], the evaluation of error sources when testing weight changes of mechanical gyroscopes [9], an evaluation of the claimed electrostatic torque effect [10] as well as a possible space drive concept [11], [12] and theoretical work on a connection between electromagnetism, mass and quantum theory [13].

As classical propulsion (force and Tsiolkovsky rocket equation, etc.) is based on Newton's mechanics, which in turn relies on inertia, it is quite straightforward to think that any new type of propulsion will probably involve a change in the inertial mass. Two main approaches have appeared so far:

1. Negative mass: If we find or create a substance with negative inertial mass, put it next to a normal positive inertial mass and allow for a force between them (e.g. by charging them up with opposite polarity), this so-called gravitational dipole will start to self-accelerate. That is a consequence of Newton's mechanics extended to negative inertia, which does not violate energy or momentum conservation as negative inertia also represents negative energy/momentum. The self-accelerating system therefore produces no net energy/momentum itself. This concept was first proposed by Forward [14] and recently even experimentally verified in an optical analog experiment with self-accelerating photons [15].

2. Variable/Oscillating mass: It may not be necessary for a revolutionary propulsion device to have negative inertial mass, it could be sufficient to have an inertial mass that is oscillating. If we imagine such a mass that we push when it is heavy and pull back when it is lighter, such a system could indeed produce a net momentum without spending propellant. As recently explicitly shown by Wanser [16], momentum conservation does only apply to a system with constant mass. Our oscillating mass system clearly violates this condition providing a method of producing real propellant-less thrust. Of course energy must be spent in order to modify mass and to push/pull it back and forth. Properly written down, also this approach does not violate any physical conservation principle.

Of course, the real challenge here is to produce macroscopic quantities of negative or oscillating inertial mass. So far, the properties of negative inertial mass have been mimicked in experiments using effective mass inside certain boundaries only (e.g. neutrons inside a crystal [17], or photons inside fibers [15]). How shall real negative mass exist outside such special boundaries? Oscillating inertial masses are much simpler to imagine. For example, charging and discharging a capacitor will change its mass by simply following $E = mc^2$. Unfortunately, c^2 is a large number so the resulting mass fluctuation will be very small. Of course the availability of high-frequency technology up to the THz range may compensate some of that if properly done.

The approach currently pursued at TU Dresden is to investigate four different possibilities to achieve negative/oscillating inertial mass as shown in Fig. 1. This paper will give an overview of the present status for each of the research lines.

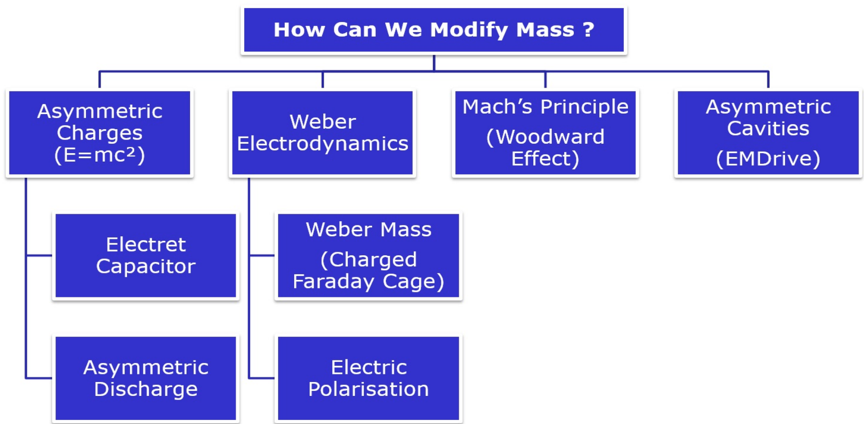


Figure 1: Mass Modification Approach

2. Asymmetric Charges

According to Einstein's famous equation $E = mc^2$, all non-gravitational sources of energy contribute to mass (the energy of the gravitational field cannot be localized according to the equivalence principle [18]). Boyer [19] showed that two opposite charges should lose weight as the electrostatic potential energy between dissimilar charges is always negative. Considering two charges, the energy of the whole system is given as:

$$U = m_1 c^2 + m_2 c^2 + \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r} \tag{1}$$

where r is the separation distance between the charges, and m and q is the respective mass and amount of charge. It is now straightforward to see that if the two charges have opposite signs, the electrostatic potential energy is reducing the total mass of the system by

$$\Delta m = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r c^2} \tag{2}$$

Of course the main question here is where this change in mass is actually localized. Is the delta-mass equally split between the charges involved, or is this delta mass only visible for the system of charges as a whole? If the actual mass of a charge would be modified, then this could open up the possibility to use this effect for our propellantless-propulsion scheme.

The contribution of electrostatic energy to mass is actually a century-old question. The simplest configuration is the one of a single electron acting on itself (self-energy). Initially J.J. Thompson derived the so-called electromagnetic mass (1881) and at the beginning of the 20th century it was thought that this electromagnetic contribution actually is responsible the whole mass of the electron. That changed of course with the development of relativity and quantum theory. Still, self-energy contributions to mass and the resulting perturbations to the classical motion of particles is an active field of research (e.g. [20]). However, self-energy contributions and contributions to each charge from multiple charge interactions are very different scenarios.

Brillouin [21] studied this question and argued that as almost all energy associated with the electric field is localized within the classical electron radius, the mass change should localize at the individual particles as well. If we consider a point-particle with charge Q, the energy of the electric field from infinity towards a radius R is defined as

$$U = \frac{1}{8\pi\epsilon_0}\frac{Q^2}{R} \tag{3}$$

Accordingly, the mass associated with that energy can be expressed as

$$M_q = \frac{U}{c^2} = \frac{Q^2}{8\pi\epsilon_0 c^2}\frac{1}{R} = \frac{Q\phi}{2c^2} \tag{4}$$

where ϕ is the electric potential. From these equations, it's clear that the mass diverges as R approaches zero and therefore a finite radius is required for the charged particle. That was how the classical electron radius was introduced. Still, the introduction of an arbitrary radius to justify that the energy of the field materializes as a mass change for every particle involved is not fully convincing.

Contrary to this classical approach that summarizes the energy from infinity towards an arbitrary radius (outside view), a more modern approach is given by the Reissner-Nordström metric which describes the field equations of a mass M with charge Q as

$$\begin{aligned} ds^2 &= \left(1 - \frac{2GM}{rc^2} + \frac{GQ^2}{4\pi\epsilon_0 r^2 c^4}\right) c^2 dt^2 - \left(1 - \frac{2GM}{rc^2} + \frac{GQ^2}{4\pi\epsilon_0 r^2 c^4}\right)^{-1} dr^2 \\ &- r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right) \end{aligned}$$

where the line element is approximated using

$$g_{00} \cong 1 + 2\frac{\Delta U}{c^2}, \quad \Delta U = -\frac{GM}{r} + \frac{GM_q}{r} = -\frac{GM}{r} + \frac{GQ^2}{8\pi\epsilon_0 c^2}\frac{1}{r^2} \tag{5}$$

This can be considered the length element inside the mass, as here we are really dealing with the equations of motion of the charged mass itself. As the gravitational potential energy is negative (mass attracts mass) but the electrostatic potential energy is positive, this charge-energy correction here acts as a negative mass component (Reissner-Nordström repulsion) at $r < R$, where R is the event horizon. We see that this is exactly opposite to the electromagnetic mass view that assigned a positive mass due to the electrostatic self-energy of the field. Bringing both views together, one may even say that indeed the motion of charged particles will be affected by the electrostatic field, but there is no net mass gain at the location of the particle as the negative contribution there is balanced out by the positive contribution due to the energy density of the field towards infinity.

Still, this question has not been experimentally assessed thoroughly. The contribution of an electrostatic potential to mass (electrostatic redshift) was experimentally investigated with a null result by Kennedy et al and Drill in the 1930s [22], [23]. Woodward and Crowley [24] pointed out that this result was to be expected using the Reissner-Nordström metric to predict the effect and the instrumentation resolution at that time. New experiments will be necessary to probe such an effect.

On the promise that electrostatic fields may influence a particle's rest mass, we recently published a configuration called the electret capacitor which could enable the utilization of this effect for propulsion purposes [11]. A capacitor typically consists of two sheets of metal with a dielectric in between. If the capacitor is charged, a certain amount of charge leaves one surface to go to the second one. Therefore, the charge density on both plates is equal but with different polarities. For the electret capacitor, two electrets (sheets of dielectrics with permanent electric charges on them) with different charge densities are opposite to each other, creating a new electrostatic situation where the positive self-energy from the interaction of charges with the same polarity can be outbalanced by the negative interaction energy between the charges with different polarities. In certain geometrical and charge density configurations, a negative energy larger than the positive rest mass energy of the charges from one side of this electret capacitor may be created, which could be used as a negative inertial mass source for propellantless propulsion.

Apart from the electric configuration, discharges in a highly asymmetric electric field may also provide the necessary boundary for charges to behave as negative inertial masses which may result in a novel propulsion scheme.

3. Weber Electrodynamics

In parallel to the development of Maxwell's equations, Wilhelm Weber proposed a force that also covered all known aspects of electromagnetism (Ampere, Coulomb, Faraday and Gauss's laws) and incorporated Newton's third law in the strong form, that is that the force is always along the straight line joining two charges [25] (which also implies the conservation of linear and angular momentum). However, Weber's electrodynamics also gives rise to new effects such as the change of the effective inertial mass of a charge inside a charged spherical shell which we could exploit for negative matter propulsion. Assis proposed an extension to Weber's electrodynamics that allows the derivation of a gravitation-type force [26], [27]. This extended model may be used to actually modify mass itself. Here we will give a short overview of both approaches.

A. Weber Mass (Charged Faraday Cage)

Weber's force expression and the related potential energy is given by

$$\boldsymbol{F} = \frac{q_1 q_2}{4\pi\epsilon_0}\frac{\hat{\boldsymbol{r}}}{r^2}\left(1 - \frac{\dot{r}^2}{2c^2} + \frac{r\ddot{r}}{c^2}\right), \quad U = \frac{q_1 q_2}{4\pi\epsilon_0}\frac{1}{r}\left(1 - \frac{\dot{r}^2}{2c^2}\right), \tag{6}$$

where q_1 and q_2 are the respective charges and r is the distance between them. If we now consider a single charge inside a charged spherical dielectric shell (in order to ignore eddy currents or mirror charges), we must integrate the force and sum up all the interaction between the single charge inside the shell and all other charges along the shell. Surprisingly, a net force remains that acts on the single charge when it accelerates inside the shell [28] given by

$$\boldsymbol{F} = \frac{qQ}{12\pi\epsilon_0 c^2 R}\cdot\boldsymbol{a} = \frac{q\phi}{3c^2}\cdot\boldsymbol{a}, \tag{7}$$

where Q is the charge on the shell, R the shell's radius and ϕ the electrostatic potential inside the shell. Classically, no force is expected on a charge inside a charged shell as the electric potential is constant and therefore no electric and no force acts on charges inside. According to Weber's electrodynamics, this force is proportional to acceleration of the charge and therefore influences the charge's inertial mass. If the total inertial mass is now the sum of the unaffected mass and the Weber mass, we may express the effective mass of the charge as

$$m^* = m - \frac{qQ}{12\pi\epsilon_0 c^2 R} = m - \frac{q\phi}{3c^2} \tag{8}$$

The equation predicts that a change in mass should be quite observable in a dedicated laboratory experiment. Considering a dielectric shell with a radius of 0.5 m charged up to 1.5 MV, we could expect to double an electron's mass – or reduce it to zero depending on the shell's charge polarity. In fact, up to a numerical factor, that result is very close to the one for the electromagnetic mass (see Eq. (4)).

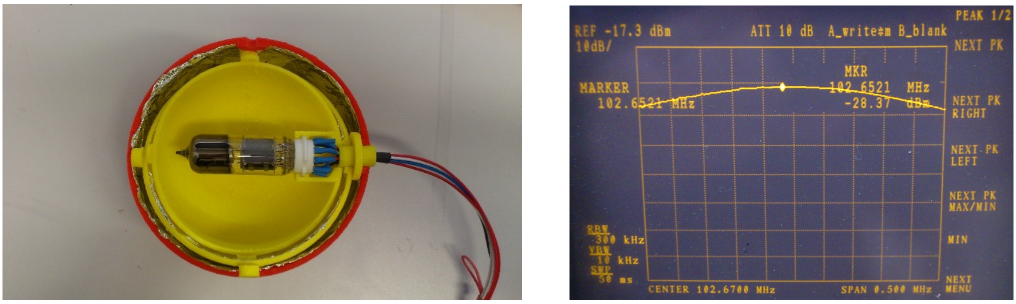
Mikhailov published a number of experiments where such an effect was indeed observed. First, he put a neon glow lamp inside a glass shell that was coated by a thin layer of GaIn and an RC-oscillator inside a Faraday shield below [29]. The coated glass shell imitates the charged dielectric shell as originally proposed by Assis. Mikhailov assumed that the frequency of the lamp is directly proportional to the electron's mass. Indeed, he observed that the lamp's frequency changed if he charged the sphere as predicted by Equ. (9) within a factor 3/2. In a second experiment, the neon lamp was replaced by a Barkhausen-Kurz generator leading to similar results [30]. Finally, the neon-lamp experiment was repeated with two charged concentric shells showing that the frequency/mass effect from charging up the first shell can be counterbalanced by oppositely charging the outer shell [31].

Junginger and Popovich [32] repeated the neon glow lamp experiment and implemented an optical counter instead of electrically measuring the frequency of the lamp – and observed a null result. Also Little et al [33] performed a similar replication and observed a null result with optical counters and observed that the electric measurement of the lamp's frequency may be influenced by the Faraday's shield potential depending on the coupling capacitor used (however the signature of the effect was a parabola instead of the linear relationship as obtained by Mikhailov). At TU Dresden, we tried to replicate Mikhailov's setup and implemented an optical counter in parallel. Indeed, we could also verify the variation that Mikhailov has seen and traced it back to influence of the coupling capacitor. Running the experiment with an optical counter also produced a null effect.

However, we then asked ourselves how representative a neon discharge is with respect to the single electron prediction from Weber/Assis. A plasma discharge produces a significant current and a number of ions in close proximity to the electrons. This setup may therefore not be representative at all in order to test this prediction. Mikhailov's second setup used a Barkhausen-Kurz generator where an electron cloud is oscillating around a grid with high frequency. This frequency f should be closely linked to the mass of the electron as given by:

$$f \approx \sqrt{\frac{e\phi}{2m}} \cdot \frac{1}{\ell} \tag{9}$$

where ℓ is the distance from the cathode to the anode. Mikhailov did not measure the frequency directly in his setup but only qualitatively. We decided to make a replication using both the same tube as well as others that are known to produce Barkhausen-Kurz oscillations. We then put the tube inside a 3D printed shell with a metallic layer that could be biased. Using an Advantest R3261A signal analyzer, the actual frequency of the tube during biasing the spherical shell could be monitored as shown in Fig. 2.



(a) Inside Charged Sphere (b) Frequency Measurement

Figure 2: Barkhausen-Kurz Generator Setup.

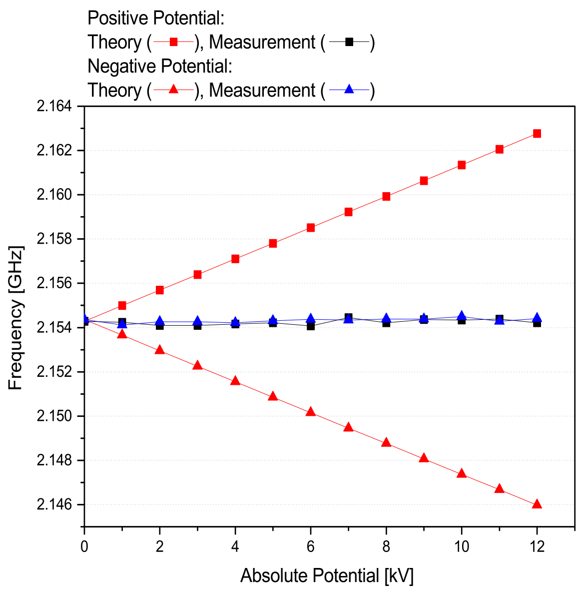


Figure 3: Observed Frequency Variation of Maximum Signal Peak (Average of Three Test Runs) with Respect to the Expected Variation according to Weber/Assis

The following observations were made (a detailed description of the experiment will be presented elsewhere):

- The original Mikhailov setup did not produce Barkhausen-type oscillations as the frequency did not scale with the square-root of the applied voltage to the grid.
- We replaced the tube and electronics successfully to observe Barkhausen-type oscillations with the correct characteristics.
- The frequency of the maximum signal peak emitted signal was tracked while varying the potential applied to the metallic sphere. The result is shown in Fig. 3.

> As it can be seen, our resolution was more than an order of magnitude better to see the predicted effect but no variation with the applied potential could be seen. However, it must be noted that the width of the signal was about 5 MHz which is in the range of the expected variation (8 MHz at 12 kV).

Of course, also here we have to ask if the experimental setup correctly represents the case predicted by Weber/Assis. For example, here we have an electron cloud instead of a single electron and the approximation of the Barkhausen oscillation in Equ. (10) also leaves room for correction factors that could possibly change our expected variation. Further experiments with different setups are necessary to look for an electrostatic influence on mass to find a definite answer.

B. Electric Polarization

Assis [26], [27] proposed an extension to Weber's electrodynamics that allowed him to derive gravitational and inertial-type forces from electrodynamics. His model is based on two assumptions:

1. Mass is composed of two opposite charges that vibrate with a certain amplitude and frequency. This can be considered a string-type approach.
2. Weber's potential Equ. (7) is actually a first order approximation valid for Maxwellian electromagnetism. Assis generalizes this equation with high-order terms as follows:

$$U = \frac{q_1 q_2}{4\pi\epsilon_0 r}\left(1 - \alpha\left(\frac{\dot{r}}{c}\right)^2 - \beta\left(\frac{\dot{r}}{c}\right)^4 - \gamma\left(\frac{\dot{r}}{c}\right)^6 \cdots\right), \tag{10}$$

where α is known as 0.5 and the other coefficients are assumed on the order of unity without knowing their precise value. Then he calculates the force between two oscillating dipoles with charge q, amplitude A and angular frequency ω by averaging over time and the three possible orientations (x, y, z) of the oscillating strings to arrive at

$$F = -\frac{7\beta}{18}\left(\frac{q_{1+}q_{2+}}{4\pi\epsilon_0 r^2}\right)\frac{A_{1-}^2\omega_1^2 A_{2-}^2\omega_2^2}{c^4}\left(1 + \frac{\gamma}{\beta}\frac{45\dot{r}^2 - 18r\ddot{r}}{7c^2}\right) \tag{11}$$

This looks like an always attractive force between the oscillators comparable with a similar $1/r^2$ dependence like gravity. The second-order correction term in the equation is identified with inertia. Of course, there are a number of free parameters (q, A, ω and the coefficients β and γ) that make it difficult to predict actual masses. However, recently we could show that this model allows the correct prediction of the maximum possible point mass which is equal to the Planck mass allowing to derive Planck's constant and the fine-structure constant with only one free coefficient [13]:

$$\hbar = \frac{h}{2\pi} = \frac{7\pi^3 e^2 \beta}{72 c\epsilon_0} = 2.92 \times 10^{-35}\beta \tag{12}$$

which matches the known value exactly for $\beta = 3.62$ (it is on the order of unity as Assis assumed). This is a remarkable result as it is the first derivation of the core assumption of quantum theory from an electromagnetic and gravitational model, providing a possible link between these cornerstones of modern physics and possibly an alternative to the Higgs model approach to explain mass.

If the Assis mass model is correct, then it may be possible to influence mass, e.g., due to electric polarization which is then influencing the orientation of the oscillating dipoles and therefore the average force between them. Apart from theoretical models to study such scenarios, we are currently testing the influence of highly polarized wax-electrets on their weight as a function of polarization and time. Similar tests were recently reported in a patent from Kita [34] where he claimed changes as high as 140 mg for samples with a weight of 278 g. We started our own wax-based electret production (45% carnauba wax, 45% resin and 10% bee wax) that were electrically polarized inside a capacitor with up to 10 kV during their cooling down phase. We used glass containers in order to limit any gas exchange with the environment which turned out to be very critical. That limited the observed weight changes in our experiments for samples with up to 200 g (including the container) to a few milli-grams only (see Fig. 4) [35]. We are presently further improving the setup in order to trace temperature and humidity changes in order to find an explanation for the observed drifts. Then we will proceed with measurements of different type of electrets or capacitors in order to investigate this mass change possibility.

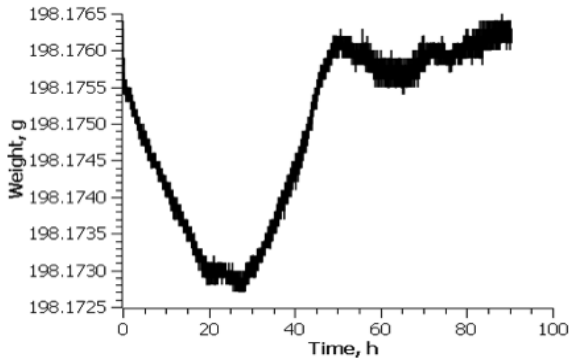


Figure 4: Weight Change of Polarized Electrets over Time [35]

4. Mach's Principle (Woodward Effect)

Mach's principle is a concept in physics that tries to explain inertia [36]. It had been a guiding principle for A. Einstein in the development of his general relativity theory. Although there are many different interpretations, a simple explanation would be: "mass out there influences inertia here". It means that every mass is connected to all the masses of the whole universe by gravitational forces, which in turn is the cause for inertia. Some consequences of Einstein's theory can be indeed viewed as Machian, like the dragging of space-time by rotating objects which then influences objects in their close vicinity.

Over many years, J.F. Woodward used Mach's principle to propose a scheme that he calls transient mass fluctuations [37], which suggests that measureable changes in the inertial mass of a body can be created due to high-frequency oscillations which are caused by a back-reaction of the universe on the oscillating test mass. His derivation is based on a flat-space, low-velocity relativistic evaluation of the four-divergence of the back-reaction field that arises from the gravitation of the universe. Here we will present a simple analysis using linearized general relativity theory that arrives at similar conclusions without any necessary assumptions.

Linearizing general relativity is an approximation scheme valid for test masses at slow velocities (with respect to the speed of light), in an environment that is not dominated by large gravitational fields (e.g. black holes), which is a good representation of our laboratory boundaries. The starting point is the Einstein field equation, where the metric tensor $g_{\mu\nu}$ is treated as flat spacetime $\eta_{\mu\nu}$ with a perturbation component $h_{\mu\nu}$:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} , \quad g_{\mu\nu} \cong \eta_{\mu\nu} + h_{\mu\nu} . \tag{13}$$

By using the definitions

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h , \quad \bar{h}_{00} = \frac{4\phi_g}{c^2} , \quad T_{00} = \rho c^2 , \tag{14}$$

it is possible to simplify Einstein's equation to

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\bar{h}_{\mu\nu} - \nabla^2 \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu} \tag{15}$$

Now, one usually takes as a first order only static solutions, which ignores the first term on the left side, that immediately leads to Newton's gravitational force law:

$$\nabla \cdot \boldsymbol{g} = -\nabla^2 \phi_g = -\frac{4\pi G}{c^2} T_{00} = -4\pi G \rho_0 \tag{16}$$

where $\boldsymbol{g} = -\nabla \phi_g$ is the gravitational force per unit mass. As we are looking for transient solutions, we will now relax the approximation for the static solution and keep the first term in Equ. (15). This then leads to a deviation from Newton's law that is given as:

$$\frac{1}{c^2}\frac{\partial^2 \phi_g}{\partial t^2} - \nabla^2 \phi_g = -\frac{4\pi G}{c^2} T_{00} = -4\pi G \rho_0 \tag{17}$$

and therefore

$$\begin{aligned} \nabla \cdot \boldsymbol{g} &= -\nabla^2 \phi_g = -4\pi G \rho - \frac{1}{c^2}\frac{\partial^2 \phi_g}{\partial t^2} \\ &= -4\pi G \left(\rho_0 + \frac{1}{4\pi G c^2}\frac{\partial^2 \phi_g}{\partial t^2} \right) \end{aligned} \tag{18}$$

By comparing Eqs. (16) and (18), we see that time-varying terms lead to a change in the body's density (or mass by integration over its volume) that is independent of the gravitational constant G, which make such terms very large compared to "static" density (mass). This structure looks similar to displacement currents in Maxwell's equations. In the introduction, we discussed the example of a capacitor that is being charged and discharged and therefore varies its mass due to $E = mc^2$, making the mass changes too small to be observed. However, Eq. (18) tells us that fast mass changes are coupling much stronger to the gravitational field (by the factor $1/G \approx 1.5 \times 10^{10}$) than static masses do, which should make this effect indeed observable.

The change in density can be expressed as

$$\begin{aligned} \delta\rho_0 &= \frac{1}{4\pi G c^2}\frac{\partial^2 \phi_g}{\partial t^2} = -\frac{\phi_g}{4\pi G c^2 m_0}\frac{\partial^2 m_0}{\partial t^2} \\ &= -\frac{\phi_g}{4\pi G c^2 \rho_0}\frac{\partial^2 \rho_0}{\partial t^2} = \frac{1}{4\pi G \rho_0}\frac{\partial^2 \rho_0}{\partial t^2} \end{aligned} \tag{19}$$

where we used $\phi_g = -Gm_0/r$ for the gravitational potential and $\phi_g/c^2 = -1$ which was derived by Sciama [38] due to the interaction of the gravitational potential throughout the whole universe, which is of course the concept of Mach's principle. This equation is similar to the one from Woodward (first order term) and clearly shows that indeed transient Mach-type fluctuations are predicted by general relativity theory without the introduction of new physics.

So far, over the years many tests have been published by Woodward's lab [37,39,40] and others [41,42]. His design is based on piezo crystals that act both as capacitors that trigger mass changes due to rapid charging/discharging, as well as accelerators to push and pull the crystals in order to get a directional thrust as outlined in the introduction. After the implementation of a torsion balance, the observed thrusts were in the sub-μN range for the models and electronics used. Many error sources were addressed such as thermal drifts or vibration artefacts.

Still, a number of shortcomings are present that we need to tackle in order to claim an experimental effect without any doubts. Most importantly, no tests were carried out up to now with the electronics (signal generator and amplifier) on the balance in order to completely rule out interactions between them. So far, all tests used electronics outside the vacuum chamber and liquid-metal contacts that connected to the thruster on the balance. We therefore decided to build vacuum-compatible electronics that can be mounted on a thrust balance to carry out thrust measurements with a fully integrated thruster-electronics package. Our test thruster is a model that was given to us in 1999 by J. Woodward which looks similar in design, however, it contains old piezo elements with non-optimal specifications so that we expect somewhat lower thrusts compared to his present models.

Our thrust balance uses flexural bearings and is similar in its design to many other low-thrust balances with several distinct differences [43], see Fig. 5:

- Up to 25 kg of thruster and electronics weight is possible, which enables the possibility of heavy shielding if necessary.
- On-board electronics and data acquisition system with infrared wireless communication, 24 V supply through the bearings, liquid-metal contacts if needed.
- Vibration damping of the whole vacuum chamber and inside the vacuum chamber
- Calibration with electrostatic combs or voice-coil
- Use of the attocube IPS laser interferometer which enables a thrust noise down to the sub-nN regime

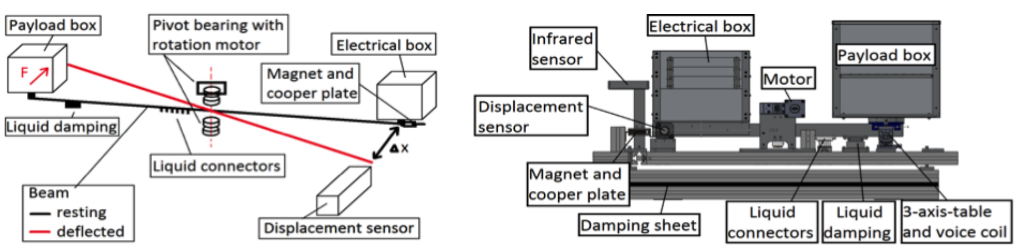


Figure 5: Thrust Balance Setup [43]

The electronics on the balance as well as the Mach-Effect thruster can be seen in Fig. 6 and the whole thrust balance inside our large vacuum chamber is shown in Fig. 7. First tests show thrust values in the sub-μN range, however, balance calibration, thermal drifts and power feeding line interactions are still under investigation before our first test campaign will be finalized.

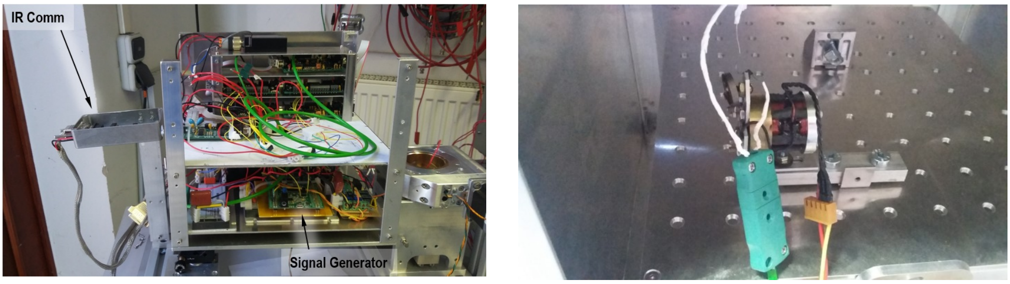


Figure 6: Mach-Effect Thruster: Setup of Electronics and Thruster Model

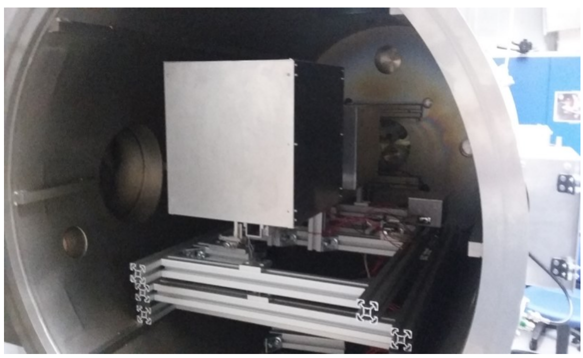


Figure 7: Mach-Effect Thruster: Setup of Thrust Balance

5. Asymmetric Cavities (EM-Drive)

The EM-Drive has been proposed as a revolutionary propellantless thruster using a resonating microwave cavity [44-46]. The inventor R. Shawyer claims that it works on the difference in radiation pressure due to the geometry of its tapered resonance cavity. This may also be interpreted as a change in the effective photon mass at each side of the cavity, which somehow resembles Woodward's transient Mach-fluctuation thruster with photons instead of piezo crystals, that may ultimately lead to higher efficiencies and thrust-to-power ratios.

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 through 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.
An overview of the different setups can be seen in Fig. 8.

Thruster Model with Magnetron | Setup with Box on Knife-Edge Balance | Setup on Thrust Balance inside Vacuum Chamber

Figure 8: EMDrive Setups

Our measurements revealed thrusts as expected from previous claims (due to a low Q factor of < 50, we observed thrusts of $\pm 20\mu$N), 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. Details of the measurement can be seen found in [5].

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 cannot 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.

6. Conclusion

This paper summarizes the current activities towards revolutionary propulsion activities at TU Dresden. We believe this is an excellent educational topic which a great learning experience for students due to its theoretical and experimental challenges. Even an experimental null result leads to a better understanding of measurement artefacts or setup limitations which are very valuable for other similar investigations (e.g. low-thrust measurements for space thrusters). Of course, research towards totally new propulsion schemes can be very valuable to ultimately push the technological limit of our present limitations in space exploration.

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Q & A Discussion

Part I

During Martin's first talk, he mention's an electret capacitor, with asymmetric charge, as a possible way of getting a negative mass

Meholic: What would happen if you discharge an electret capacitor?

Tajmar: Well, I can't exactly discharge it, because to discharge I would need to connect the capacitor to a conductive circuit, and the electret is made of an isolator. So I have an isolator, and I'm bombarding it with ions or electrons which just stick to the surface. There is no current flow.

Meholic: How are you going to extract the usefulness of the negative mass out of that electret construct?
Tajmar: That's coming up in the next slides. By the way, if I get this to work I'll have a negative mass I can walk around with and I can sell it by the negative kilogram!

... audience laughter....

Fearn: During the Weber Electrodynamics section of the 1st talk, Martin describes the Wilhelm E. Weber force law, which just depends on charges, their separation, and velocity. It was a good enough description to derive the speed of light. It appears that Weber's force law does not take into account radiation reaction, which is very tiny and may have been overlooked at the time. Weber may not have known about it.

Tajmar: Yes, I'm coming to that, there was a later extension by A. K. T. Assis `http://www.ifi.unicamp.br/~assis/Pramana-J-Phys-V55-p393-404(2000).pdf` which adds in additional terms. Also, it turns out that massless charged particles don't radiate, this is apparently a new research topic, for example `https://arxiv.org/abs/hep-th/0212286`.

Part II

Martin starts to talk about EM-drives...

March: You should treat this as an RF system, not an analog audio system. You need to have a dual directional coupler to your RF source and the test article. You need to look at the reflected power from the cavity and use the minimum of the SWR power tracker as a frequency tracker with an arbitrary ± offset.

Tajmar: That would be the ideal way to do it, and that's what we will try to implement next year. Certainly tracking the frequency is something that needs to be done and we have not set that up yet.

Martin starts to talk about Woodward's Mach Effect thruster work. Martin has an old thruster, Jim gave him from 1999, that he has started to run tests on. The new devices Jim runs only requires one frequency, the older devices needed two frequencies to be present, since they did not have electrostriction.

Rodal: The usual thing "now" is that Jim inputs an excitation frequency f, within f_{op}/Q_m bandwidth of the first natural frequency $f_{op} \sim 34$ KHz due to the piezoelectric effect, and that the electrostriction of the material naturally provides an excitation at $2f$, twice the excitation frequency f. However, note that the electrostiction resonance occurs at $(1/2)f_{op}$, at half the piezoelectric natural frequency f_{op} so that $2f = f_{op}$ and that the electrostriction resonant amplitude is orders of magnitude lower amplitude than the piezoelectric resonance.

Woodward: It's more complicated in this case José, because the thruster that Martin is checking is not like the ones that Heidi and I are running now, or like the ones tested by Nembo and George (they have newer devices). We are all using devices based on the Steiner–Martins SM-111 material, which has electrostriction as well as exhibiting the piezoelectric effect. The stack that Martin has, is made of EDO corporation (an American company now acquired by ITT corporation in 2007) EC-65 material discs. I don't know if that has any electrostriction response so he has to input two frequencies. It's a soft PZT material with a high dielectric constant of around 5000, it has about 4% dissipation. I built the stacks out of this stuff back then (1999) because it was cheap, they were a gift...

...audience laughter...

Woodward: Martin has shown his preliminary results, that show a small thrust from the old 1999 device. This was the first measurement of a self sustained system, with power and amplifier on board the torsion balance, to show thrust, with a very high resolution.

...audience applause...

March: Jim, didn't one of your early papers have a prediction for the thrust level in these older devices?

Woodward: No, not a paper that I recall, but there may be a graph in my "Making stargates and starships" book, that plots a thrust curve against various input power levels. Usually these devices had a small thrust measured in μN.

Tajmar: We were expecting μN or sub-μN levels of thrust, and that is what we saw in this preliminary data.

Woodward: Your data clearly shows the switching transients, tomorrow I'll show you what happens when you switch DC power on/off ... that is to say the switching transients go away. Thank you Martin !

Tajmar: You're welcome.

Martin is talking about his first data sets for the EM drive that his students built and shows data, (time stamp 00.38.25)

Rodal: Why does the thrust increase from 15 to 40 seconds?

Tajmar: Well I believe in this case, it is simply a shift in the center of gravity as the copper cavity expands. So it is an artifact of the thermal expansion of the copper.

When I turn off the power, the force stops, you see the displacement sensor shifting down slowly, as the copper cools off. But this cannot be a force, since the power is off.

Williams: You said at the end that you could not confirm the existence of thrust for the EM drive, why is that?

Tajmar: When my "null" measurement, (which is in a direction perpendicular to the forward and backward direction) gives me the same thrust reading as a forward (or +) force direction measurement, then I know I have reached the level of resolution of my experiment. I cannot then say for sure that what I have seen is real or some noise. I need to improve my experimental setup (next year) and try again with higher resolution.

Broyles: Are you planning to change the design of your EM drive in the test run next year? If so, what design are you planning to use?

Tajmar: That's partly why I am here at this workshop. I wanted to ask if this or that is a good idea to try... we need to learn from each other, to avoid repeating the same mistakes.